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ACOUSTIC METHODS FOR MEASURING THICKNESS OF OIL ON WATER

By:

A.M. Nawwar
A. Godon

Arctec Canada Limited

H.W. Jones
E. Yeatman
J. Ohuja

H.W. Jones & Associates

M.B. Frish
I. Arvin

Physical Sciences Incorporated

ARCTEC CANADA LIMITED,
311 Legget Drive,
Kanata, Ontario.
K2K 1Z8

distributed by:
INFOPALL
Bay 105, 4116 - 64th Avenue S.E.
Calgary, Alberta, Canada T2C 2B3
Phone (403) 236-2344
Telex 03-821172 CGY
PALLISTER RESOURCE MANAGEMENT LTD.

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FOREWORD

The work reported herein was performed by Arctec Canada Limited, Kanata, Ontario, in collaboration with H.W. Jones and Associates, Tantallon, Nova Scotia, and Physical Sciences Inc., Andover, MA (USA). The following persons from the respective organizations have contributed to this study.

Arctec Canada Limited:	A.M. Nawwar A. Godon
H.W. Jones & Associates:	H.W. Jones E. Yeatman J. Ohuja
Physical Sciences Incorporated:	M.B. Frish I. Arvin

It should be stated that H.W. Jones & Associates have contributed the section on Surface Acoustic Waves, and that Physical Sciences Inc. have contributed the section on Frequency Dependent Techniques.

TABLE OF CONTENTS

Page

Foreword.....iii

Summary.....1

Résumé.....3

Introduction.....5

Surface Acoustic Waves.....8
- Acoustic Properties of Crude Oil.....8
- Rayleigh Waves.....19
- Lamb Waves.....23
- Generation and Detection of Coupled Waves.....31
- Pilot Experiment.....34
- Other Acoustic Methods.....39

Frequency-Dependent Technique.....40
- Approach.....40
- Calculation of Reflection Coefficients.....40
- Potential Measurement Techniques.....45
- Broad-Band Frequency Distribution.....45
- Frequency-Scanning Techniques.....47

Conclusions.....51

Recommendations.....53

References.....54

Bibliography.....56

LIST OF TABLES

1. Experimental results of Rayleigh wave detection.....36

LIST OF FIGURES

Figure		Page
1.	Real and imaginary components of the shear mechanical impedance of a lubricating oil	10
2.	Real and imaginary components of the shear mechanical impedance of crude oil	11
3.	Shear velocity versus wavelength in oil	14
4.	Shear velocity versus frequency in oil	14
5.	Shear attenuation versus frequency for oil of viscosity 5 poise	15
6.	Shear attenuation versus frequency for oil of viscosity 50 poise	15
7.	Viscosity of Beaufort sea crude oil versus temperature	17
8.	Viscosity of Khafji crude oil versus weathering time	18
9	Oil viscosity versus evaporation	18
10.	Displacement patterns	20
11.	Typical normalized displacement for a Rayleigh wave	20
12.	Rayleigh wavelength in crude oil versus frequency	22
13.	Rayleigh wave velocity in crude oil versus frequency	22
14.	Displacement patterns	25
15.	Partial wave patterns	25
16.	Propagation velocity of Lamb waves versus wavelength for an oil thickness of 10 microns	27
17.	Propagation velocity of Lamb waves versus wavelength for an oil thickness of 100 microns	27
18.	Propagation velocity of Lamb waves versus wavelength for an oil thickness of 1 mm	28
19.	Propagation velocity of Lamb waves versus wavelength for an oil thickness of 1 cm	28
20.	Partial wave patterns for transverse resonance	30
21.	Excitation of surface acoustic waves on a solid substrate	32
22.	Generation of SAWs using a compressional wave/wedge technique	32
23.	Experimental set-up with a straight barrier	35
24.	Experimental set-up with a curved barrier	38
25.	Illustration of reflection and transmission of acoustic waves incident upon a layer of oil floating on water	41
26.	Reflection coefficient plotted as a function of non-dimensionalized frequency	44
27.	Effect of changing the acoustic impedance of oil	46
28.	Spectrum of acoustic energy generated by irradiating a water surface with a focused, pulsed CO_2 laser	48
29.	Illustration of mechanism by which low-frequency modulation of reflected energy can be created	50

SUMMARY

The knowledge of the thickness of oil slicks floating on water is a primary requirement to establishing the amount of oil and, hence, to deciding on appropriate spill countermeasures. In this study, acoustic methods for measuring oil thickness on water have been considered. Two techniques have been investigated. The first uses surface acoustic waves whereas the second employs frequency dependence of the amplitude of reflected acoustic energy.

The study of surface acoustic waves (SAW) consisted of two parts: a theoretical investigation to assess the feasibility of using surface acoustic waves and an initial exploratory experimental program to generate and detect Rayleigh waves in oil. In the theoretical investigation the relevant characteristics of the oil and the expected characteristics of the surface- and layer-type waves are described. Investigations of the theory of propagation of acoustic waves, in layers of finite thickness, have shown that a measurement of oil thickness is at least possible. It appears likely that when the wavelength of the acoustic disturbance is greater than the oil thickness, the water substrate will leak away much of the energy. This leakage should be detectable using a continuous-wave amplitude measurement technique, which should not require sophisticated circuitry.

The main thrust of the experimental program was to attempt to generate surface acoustic waves of a type called Rayleigh waves in oil by taking advantage of the visco-elastic properties of the oil, and then to establish the dependence of propagation characteristics on oil-layer thickness. In this way the feasibility of a frequency-based, acoustic, thickness measurement could be assessed.

Several methods, which are used to generate surface acoustic waves in solids, were investigated but it was found that they could not easily be used to produce surface acoustic waves in oil. Instead a direct transduction technique, and surface-breaking discontinuity, was used to generate Rayleigh waves. The discontinuity was produced by using a hydrophone, to project compressional waves at a thin metal strip placed at the oil surface.

A limited-scope experimental study was undertaken to determine the initial feasibility of the technique and to establish whether a more comprehensive experimental program was justified. The results of the experiments that were conducted with this technique are described. The results are encouraging in that the presence of an oil layer was clearly demonstrated. However, actual measurement of the oil thickness was not accomplished because of the limited scope of the experiment. It should be borne in mind that this was only intended to be an initial, limited-scale, experimental study to determine whether more comprehensive experiments were justified.

The other technique was concerned with ultra-high-frequency methods which rely on changes in the acoustic reflectance of oils on water. The reflection coefficient of an oil layer 1-10 mm thick was calculated for typical properties of air, water, and oil. It has been shown that the change in the overall reflection coefficient of the oil is small and is dependent on the acoustic impedance of the oil. If this change could be measured then the acoustic impedance and speed of sound in oil could be determined and, by measuring the corresponding frequencies at which the reflection coefficient is minimized, the oil thickness could be determined.

External sound generation using laser pulse or ultrasonic waves were considered. The laser-generated sound was found to be inadequate because of spectral reproducibility and noise problems. Ultrasonic wave techniques using appropriate frequency-scanning techniques appears to hold promise. Two analysis techniques have been proposed. The first uses a variable-frequency, monochromatic, acoustic source in which the amplitude of the reflected sound waves can be measured accurately using lock-in amplifiers. The second technique uses a rapidly modulated frequency source and rapid scanning of the reflection coefficient. The latter technique holds most promise for the present application.

As a result of this study, it is recommended that further investigation be carried out to pursue the surface acoustic waves technique at a more advanced experimental level, and also to consider frequency-scanning techniques to measure the change in reflectance resulting from the presence of oil. The latter would be remotely applicable, whereas the former requires the use of disposable sensors.

RÉSUMÉ

Lors de déversements de pétrole en mer, il est nécessaire de connaître l'épaisseur des nappes d'huiles flottantes afin de mesurer la quantité de pétrole répandue et de là, choisir les contre-mesures appropriées. La présente étude traite de la mesure de l'épaisseur de l'huile flottante par des méthodes acoustiques et porte sur deux techniques. La première utilise les ondes sonores de surface, tandis que la seconde utilise la dépendance de l'amplitude de l'énergie sonore réfléchie par rapport à la fréquence.

L'étude des ondes sonores de surface comportent deux parties : une recherche théorique de la faisabilité de l'utilisation des ondes sonores de surface et un programme expérimental exploratoire initial afin de générer et de détecter des ondes Rayleigh dans le pétrole. La recherche théorique décrit les caractéristiques pertinentes de pétrole ainsi que les caractéristiques prévues des ondes de surface et de couches. Les recherches sur la théorie de propagation des ondes sonores dans des couches d'une épaisseur finie ont démontré que la mesure de l'épaisseur des nappes d'huile, le substrat aqueux perdra une grande partie de l'énergie. Cette perte devrait être décelable à l'aide d'une technique de mesure de l'amplitude des ondes continues qui ne devrait pas exiger un ensemble de circuits élaboré.

Le but principal du programme expérimental consistait à tenter de produire, dans les nappes, des ondes sonores de surface d'un type nommé ondes de Rayleigh grâce à la viscosité et à l'élasticité de l'huile et de déterminer ensuite la dépendance des caractéristiques de propagation en ce qui a trait à l'épaisseur de la couche de pétrole. De cette manière, il est possible d'évaluer de faisabilité d'une mesure acoustique de l'épaisseur basée sur la fréquence.

Plusieurs méthodes de production d'ondes sonores de surface dans les solides ont été étudiées et l'on a constaté qu'elles ne pouvaient pas être utilisées facilement pour produire des ondes sonores de surface dans le pétrole. À la place, une technique de transduction directe et de discontinuité de surface a été utilisée pour produire des ondes Rayleigh. La discontinuité a été produite par un hydrophone afin de projeter des ondes de pression sur une mince bande métallique posée à la surface de l'huile.

Une étude expérimentale de portée limitée a été entreprise afin de connaître la faisabilité initiale de la technique et de savoir si un programme expérimental plus étendu était justifié. Les résultats des expériences utilisant cette technique sont décrits. Les conclusions sont encourageantes puisqu'elles démontrent clairement la présence d'une couche d'huile. Cependant, la portée limitée de l'expérience n'a pas permis de procéder à la mesure effective de l'épaisseur de l'huile. Il faut se rappeler que cette recherche ne devait être qu'une étude expérimentale initiale, d'une portée limitée, permettant de déterminer si des expériences plus poussées étaient justifiées.

La seconde technique utilise des méthodes à ultra-haute fréquence qui se fondent sur des variations du coefficient de réflexion des huiles sur l'eau. Le coefficient de réflexion d'une couche d'huile d'une épaisseur de 1 à 10 mm a été calculé en fonction des propriétés typiques de l'air, de l'eau et de l'huile. On a démontré que le changement dans le coefficient général de réflexion du pétrole est faible et dépend de l'impédance acoustique de l'huile. Si ce changement pouvait être mesuré, l'impédance acoustique et la vitesse du son dans l'huile pourraient alors être déterminés et, en mesurant les fréquences correspondant au coefficient de réflexion minimal, l'épaisseur de l'huile pourrait être connue.

La production externe de son à l'aide de pulsations de laser ou d'ondes ultrasonores a été examinée. On a trouvé que le son produit par laser ne convenait pas à cause de problèmes reliés à la reproduction spectrale et au bruit. Les techniques basées sur les ondes ultrasonores et utilisant des méthodes appropriées de balayage des fréquences semblent prometteuses. Deux techniques d'analyse ont été proposées. La première utilise une source acoustique, monochromatique, à fréquence variable pour laquelle l'amplitude des ondes sonores réfléchies peut être mesurée avec précision à l'aide d'amplificateurs enclenchés. La seconde technique utilise une source de fréquence à modulations rapides et un balayage rapide du coefficient de réflexion. Cette seconde technique est celle qui offre le plus de possibilités dans la situation présente.

À la suite de cette étude, il est recommandé qu'une recherche plus poussée soit faite afin d'explorer la technique des ondes sonores de surface à un niveau expérimental plus avancé et qu'on étudie également les techniques de balayage de fréquences afin de mesurer les changements du coefficient de réflexion en présence d'huile. Cette dernière recherche serait difficilement applicable alors que la première exigerait l'utilisation de détecteurs jetables.

INTRODUCTION

To assess the requirements for application of dispersants, or other countermeasures, in the event of an oil spill, knowledge of the spill volume is needed. This includes the aerial coverage, thickness, number, and location of oil slicks. Systems currently in use involve sorbents and require physically reaching the oil, and, hence, are slow and inefficient. Therefore, the need exists for a capability to measure the thickness of an oil slick from a low-flying aircraft. The aerial coverage, numbers, and distribution of oil slicks can readily be determined. This measuring capability (system or sensor) should offer certain general characteristics.

a) Reliable and remote operation from an aircraft should provide speed and efficiency.

b) Because the type of oil can be quite variable, the system should be independent of the specific characteristics of the oil.

c) Because the slick dimensions on the open ocean are variable, the system should have a resolution of a few metres (the smaller, the better) and be able to integrate over an area greater than 100 m^2.

d) Because the slick thickness may vary in a wide range, the target range for the system which reflects the most likely natural occurrences may be defined from 10 μm to 10 mm.

e) The sensor should have a look angle of about 20 degrees half-angle.

f) The sensor should be readily calibrated using a simple reference source.

Several sensor types have been proposed and have undergone different levels of development. These include laser fluorosensors, infrared, radar, and passive microwave sensors. Although these methods satisfy some of the stated requirements, the need still exists for a technique or a sensor that can be used in a wider range of conditions. This prompted the Environmental Studies Research Funds to seek other innovative methods that may have application in this field.

Several techniques using laser-induced fluorescence are now available for remotely locating and characterizing oil slicks floating on oil or ice (Till and O'Neil 1985). The laser fluorosensor can also be used to measure the thickness of oil slicks as thick as a few tens or hundreds of microns (Hoge and Swift 1980). However, because of the rapid attenuation of the laser power as it propagates into the oil, fluorescence can be neither excited, nor detected, at greater depths in the oil layer. Thus, fluorescence is not a practical technique for measuring the depths of modestly thick oil slicks within the range under consideration.

Microwave systems can also be used to detect the presence of oil on water. Two mechanisms allow this: first, the smoothing effect of oil on the ocean surface roughness that reduces emissivity, and second, the direct change of the water surface's scattering and emission of energy because of the presence of oil (C-Core 1981). There are two types of systems; passive microwave systems, which measure the target's emission of natural radiation, and active systems, principally radar, which transmit energy to the target surface and measure the energy returned. Oil is detected by contrast with open water and can appear lighter or darker than the open water depending on the sea state. Oil slicks can be detected even in rough seas although the detection capability decreases as the sea state increases. Microwave systems can also operate day or night. The minimum oil film thickness detectable by passive microwave system is is about 100 microns in calm water conditions. The microwave emission characteristics of oil slicks vary with type. However passive microwave systems can only make qualitative assessments of oil thickness.

It has been found that oil thickness as thin as 1 micron can be detected by active microwave systems but that increasing thicknesses have little influence on the signal strength or quality.

Thermal sensors have been used in detecting oil slicks. They operate on the principle that the oil layer will be at a different temperature than the water because of the tendency of oil to absorb solar radiation. An open-water surface must be available to compare the contrast in image. During testing of thermal sensors, Garret and Tidmarsh (1985), found that the high sensor resolution needed to detect oil, also detected ice crystals, bubbles, and snow flakes on the water surface, which made it difficult to distinguish the oil in the images produced. However, one can usually distinguish a thin oil film from a thick layer.

Infrared sensors analyze the reflected radiation in the infrared zone and thus can distinguish oil from water. Active infrared systems irradiate the oil/water surface with infrared energy (usually using a CO_2 laser) and they measure the reflected signal while passive systems measure the ambient radiation reflected from the oil/water surface. There are few active systems - generally they can only receive a one dimensional signal while the passive systems can receive a two dimensional signal. Infrared sensors can differentiate between areas of thick oil and thin oil in the same slick but accurate qualitative measurement is not possible, McColl (1987). Infrared systems can detect oil at high altitudes (>3000m) but as altitude increases the atmosphere tends to interfere with the contrast between oil and water, O'Neil et al (1983).

Acoustic methods may be considered for this purpose because acoustic waves suffer little attenuation over the depths that are of interest. The feasibility of using acoustic methods for remote measurement of oil thickness have been examined, and the detailed investigations are presented in this report.

Two techniques have been investigated. The first technique uses surface waves, whereas the second employs frequency dependence of the amplitude of energy reflected at the oil surface layer.

The use of surface acoustic waves for measurements in this context implies that physical property differences between oil and water are significant and that this difference will provide the information that is required. The principle of measurement simply stated is that the oil has a shear modulus and water does not. One of the consequences of this fact is that the surface acoustic waves called Rayleigh waves can be transmitted in an oil layer but that they will not exist in the water below the oil. This fact can, in principle, be used to provide two pieces of information; first the existence of oil, and second, its thickness.

If surface acoustic waves (SAW) were to be used for measuring oil thickness, a device would be needed to create and measure them. Such a device would have to be in contact with the oil, but if a simple, cheap design could be achieved then it would be possible to produce a single-use, disposable instrument that could be dropped from an aircraft to transmit its information back by radio.

The operating principle of the second technique, the frequency-dependent technique is that because the acoustic impedance of the oil layer differs from that of the substrate, the layer should act acoustically similar to optical anti-reflection or dichroic coatings often found on eyeglasses, camera lenses, or precision optical devices.

The wave deflected from the upper surface of the oil layer would interfere with the waves reflected from the interfacial surface. If the path length through the oil layer were an integer multiple of the wavelength of sound in the oil, then the waves would interfere constructively. Conversely, if the path length were exactly one-half wavelength, then destructive interference would result. Thus, the frequency dependence of the amplitude of the reflected energy would contain information about the thickness of the oil layer. The fundamental question that was addressed in this study was whether or not this information could be extracted by practical means.

Both techniques, surface acoustic waves and frequency scanning, are discussed in detail in the following chapters followed by conclusions and recommendations.

SURFACE ACOUSTIC WAVES

ACOUSTIC PROPERTIES OF CRUDE OIL

To conduct a detailed theoretical examination of the possibilities of producing Rayleigh waves on oil, it was first necessary to establish fully the acoustic characteristics of the oil in question. The major part of this task involved ascertaining the shear response of crude oil. The only compressional wave characteristic needed was the wave speed, because the compressional response is frequency independent over a wide spectral range. This speed was measured by a time-of-flight technique and was found to be 1450 $\pm$ 30 m/s at room temperature and using motor oil W50. The shear response, however, is dispersive so that wave speed, wavelength, and attenuation had to be established as functions of frequency over a wide range. Once these functions had been determined, the Rayleigh wave characteristics could be calculated.

Several studies have been reported in the literature that deal with the shear mechanical properties of visco-elastic substances. Initially these were concerned primarily with the exploration of the properties of polymers. More recently, work has been done on the high-frequency shear mechanical impedance of lubricating oils, with application in the lubrication of high-speed machinery. All these studies used either chemically specific compounds or highly refined products containing a fairly limited range of molecular weights. However, Jones and Yeatman (1985) studied the shear properties of crude oil in conjunction with a major project to develop an ultrasonic method for the detection of oil spills under ice. In that study they measured the real and imaginary components of the shear impedance of "weathered" crude oil as a function of frequency and temperature. Experimental restrictions allowed only a limited number of frequencies to be measured. However, comparison with the more widely ranging measurements reported in the general literature on lubricating oils, and extrapolation based both on this comparison and on theoretical models, have extended the range of available data.

The simplest theoretical models for complex shear impedance of visco-elastic substances assume a single relaxation frequency. For frequencies much less than this value, the real and imaginary components of the shear impedance, R and X, are about equal, and increase with the square root of frequency. For frequencies far above the relaxation frequency, the real component continues to rise but levels off at a maximum value. The imaginary component reaches a peak at the relaxation frequency, and then drops to zero, which corresponds to purely elastic behaviour. The relaxation frequency can be normalized with respect to viscosity, so that the shear impedance for a variety of liquids can be displayed with a single set of curves.

In the simplest model, the Maxwell model, the relaxation frequency is given by:

$$f_r = \mu/2\pi\eta \qquad (1)$$

where η is the shear viscosity and μ the shear elasticity. For refined hydrocarbons, however, and certainly for crude oil and semi-refined products, there is a range of molecular weights and a variety of relaxation mechanisms, particularly in the case of polymers. In these situations, a single relaxation frequency is not a realistic approximation, and we are faced instead with a relaxation spectrum, the width of which depends on the chemical composition of the fluid. Because crude oils contain a wide range of components, they have particularly wide relaxation spectra, and it becomes difficult to build accurate theoretical models of the shear behaviour.

Fortunately, experimental methods exist for making measurements of the complex shear impedance. The method used in the study of crude oils was one originally developed by Mason et al. (1949), and later refined by Barlow and Lamb (1959). It involves propagating shear waves in a specially cut bar of fused quartz so that they reflect from the top surface at a grazing angle. The change in amplitude and phase of the received signal is measured when oil is added to the reflecting surface, and from these values R and X are calculated. Figure 1 shows the experimental results of Barlow and Lamb for a low-viscosity lubricating oil.

In their experiment with Arctic crude oil, Jones and Yeatman (1985) employed two operating frequencies: 1 MHz and 10 MHz. Measurements were made at various temperatures from 20°C to -20°C. The variation with temperature is quite small above 0°C; below this the viscosity changes so rapidly with temperature that it becomes extremely difficult to stabilize the temperature sufficiently to gain precise readings, particularly of phase. Extrapolation below the experimental frequency range was done using the theoretical approximations, while interpolation and higher-frequency extrapolation was done by matching the experimental results to those reported by Barlow and Lamb in their study on lubricating oils. The experimental results of Jones and Yeatman (1985) are reproduced in Figure 2. The curves present values of the real and imaginary components of the shear impedance of crude oil as functions of $\log(\alpha f)$; where α is the ratio of the oil viscosity at the measured test temperature to that at a reference temperature, normally the room temperature which is 20°C, and f is the sound frequency. Therefore, the effect of temperature is implicit in these curves. Also, for a fixed value of this parameter (αf) various combinations of oil viscosity and frequency are possible.

The shear impedance data can be used in a straightforward way to obtain dispersion curves for shear waves; that is, curves showing the relationship between frequency and wave number or wavelength.

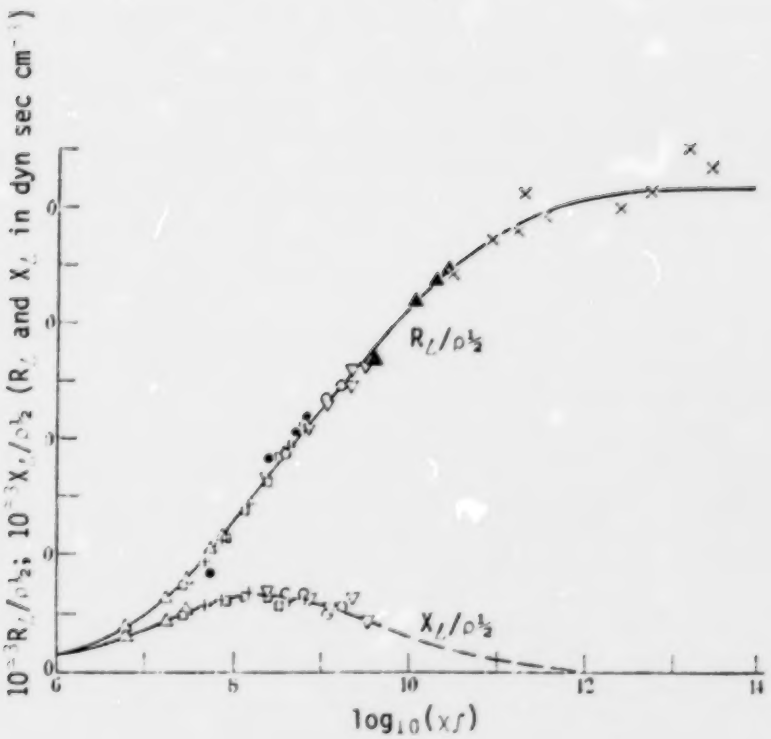

Fig. 1. Real and imaginary components of the shear mechanical impedance of a lubricating oil, as a function of frequency; α = viscosity at temperature of measurement divided by viscosity at 20° C (from Barlow and Lamb 1959).

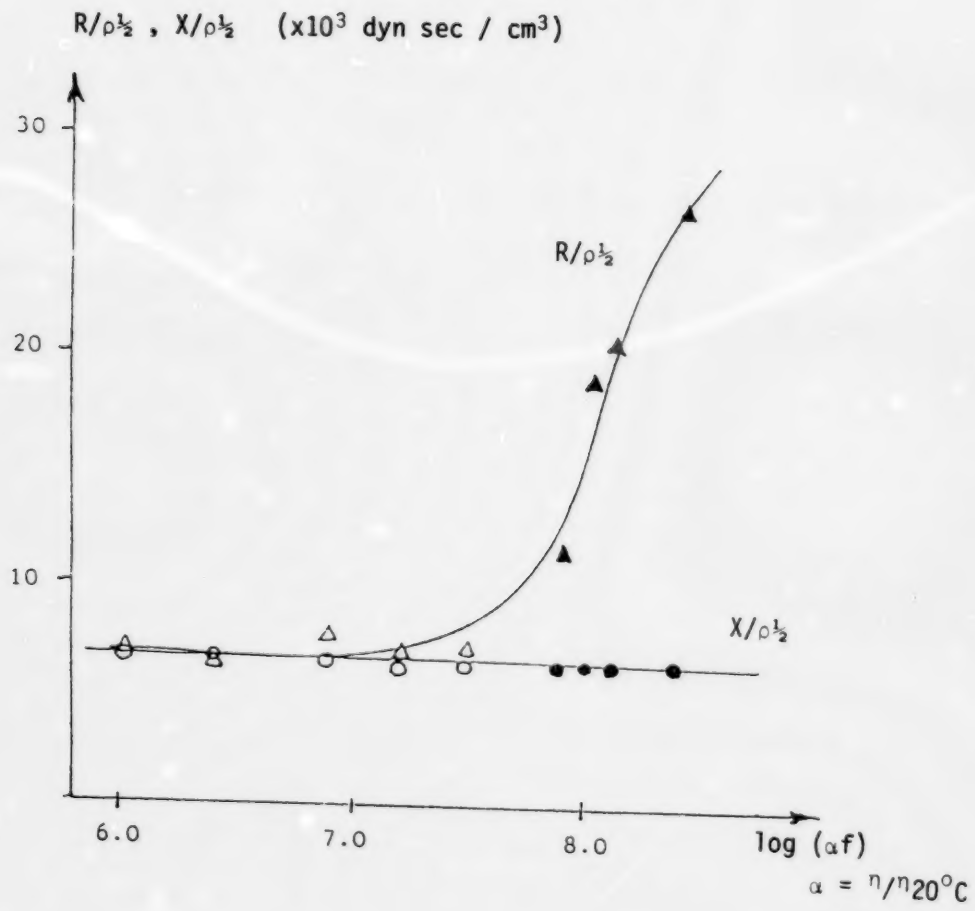

Fig. 2. Real and imaginary components of the shear mechanical impedance of crude oil, as a function of frequency (from Jones and Yeatman 1985).

Because the complex impedance is known, attenuation as a function of frequency can also be determined. Propagation velocity (group velocity) and phase velocity are available directly from the dispersion relations. The relationships among these various quantities can be explained in the following way.

Let us define a complex shear velocity for the material, C^*. This is related to the complex shear modulus, G^*, in the following way:

$$C^* = (G^*/\rho)^{1/2} \qquad (2)$$

where ρ is the density of the medium.

When the shear impedance, rather than the shear modulus, is known, we can use the usual expression for acoustic impedance, Z^*, as a function of density and the speed of sound:

$$Z^* = \rho C^* = R + iX . \qquad (3)$$

Thus, we can see that the complex shear velocity is simply the impedance divided by the density. From the velocity, we can determine the wavelength, λ, or the complex wave number, $k^* = 2\pi\lambda$, using:

$$k^* = \omega/C^* \qquad (4)$$

where $\omega = 2\pi f$ is the angular frequency. The complex wave number is particularly useful as the real and imaginary components correspond directly to the characteristic propagation and attenuation lengths. Thus, if $k^* = k_r + ik_x$ then:

$$k_r = \frac{\rho\omega R}{R^2 + X^2} \qquad (5)$$

$$k_x = \frac{-\rho\omega X}{R^2 + X^2} . \qquad (6)$$

If we look at the normal expression for a propagating plane (acoustic) wave:

$$p = p_o e^{i(\omega t - kz)} \qquad (7)$$

then in the case of a complex wave number this can be expressed as:

$$p = p_o e^{i(\omega t - k_r z)} e^{-k_x z} \qquad (8)$$

From this we see that k_x is the attenuation factor, or the reciprocal of the distance of propagation resulting in attenuation of 1/e or 8.7 dB.

Figures 3 through 6 show the relationships between shear velocity, wavelength, attenuation factor, and frequency, which were computed from the oil shear impedance data using the relationships above.

One of the principal effects of the visco-elastic properties of the oil is that the velocity drops sharply with decreasing frequency below a certain frequency range, as seen in Figure 4. The result is that the wavelengths do not increase nearly as rapidly as would be expected for a linear (elastic) medium. Thus, to get the wavelengths required to interrogate the oil layers we need to move into a frequency range below the regime in which experimental measurements were made by Jones and Yeatman (1985) for crude oil or by Barlow and Lamb (1959) for lubricating oils.

In this low-frequency regime, the results shown are based on theoretical models for the shear response that primarily consider the medium to have a single, well-defined relaxation frequency. This is not the case for refined oils and certainly not for crude oils. The result of these considerations is that it may well be that at such low frequencies the heavier (large molecular weight) components of the oil may carry the oscillations independently, so that the velocities and thus the wavelengths will be substantially greater than those predicted here. In addition, the attenuation would certainly be reduced by such a phenomenon. However, this statement would require further experimental verification.

Because the calculated properties of crude oil were based on the shear impedance curves, and the latter were determined as functions of the parameter (αf), changes in oil viscosity, for instance those resulting from weathering, may be considered as numerically equivalent to a shift in frequency.

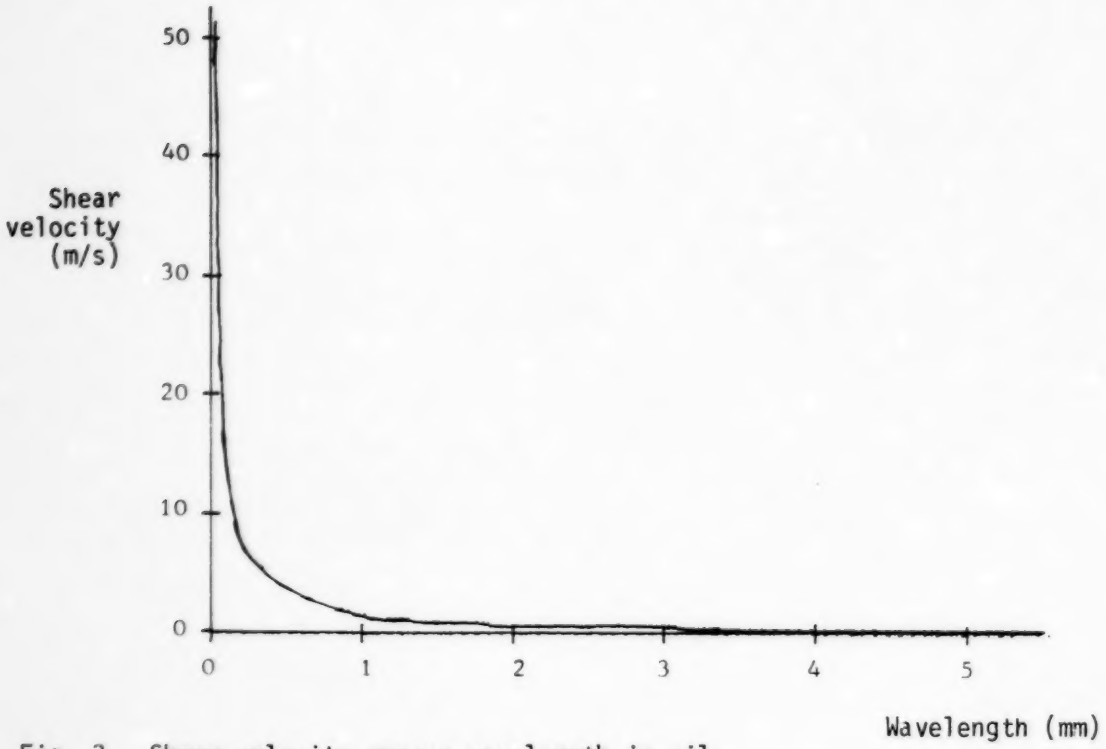

Fig. 3. Shear velocity versus wavelength in oil.

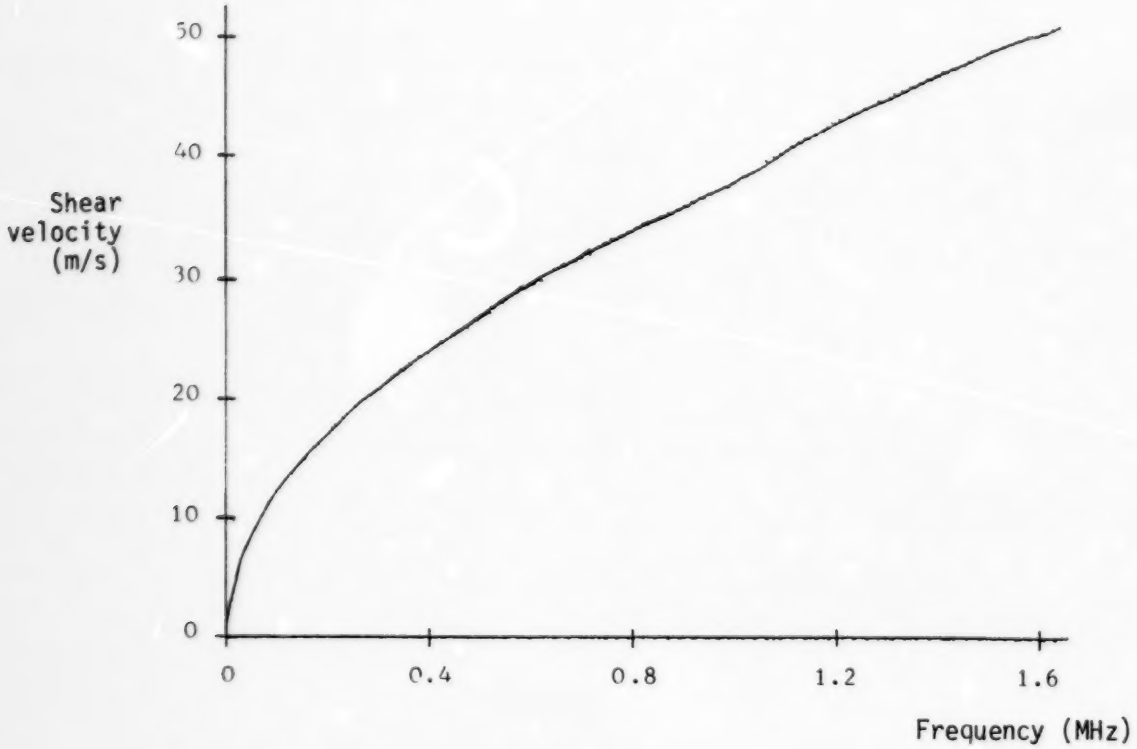

Fig. 4. Shear velocity versus frequency in oil.

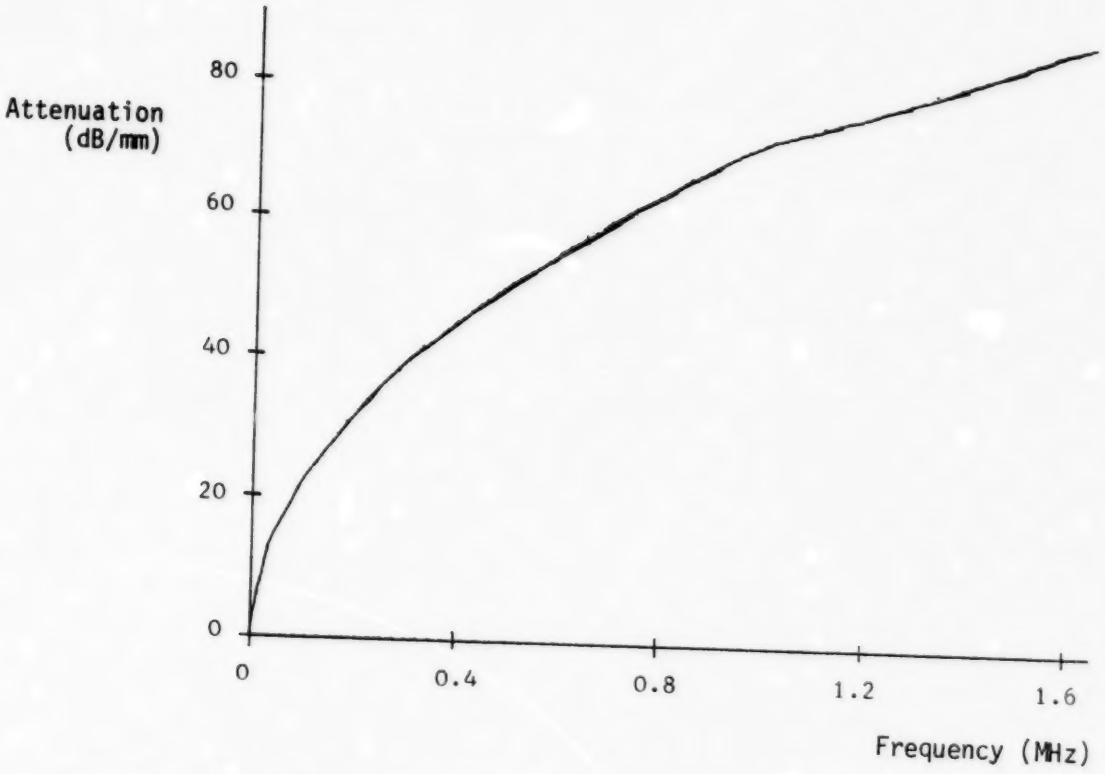

Fig. 5. Shear attenuation versus frequency for oil of viscosity 5 poise.

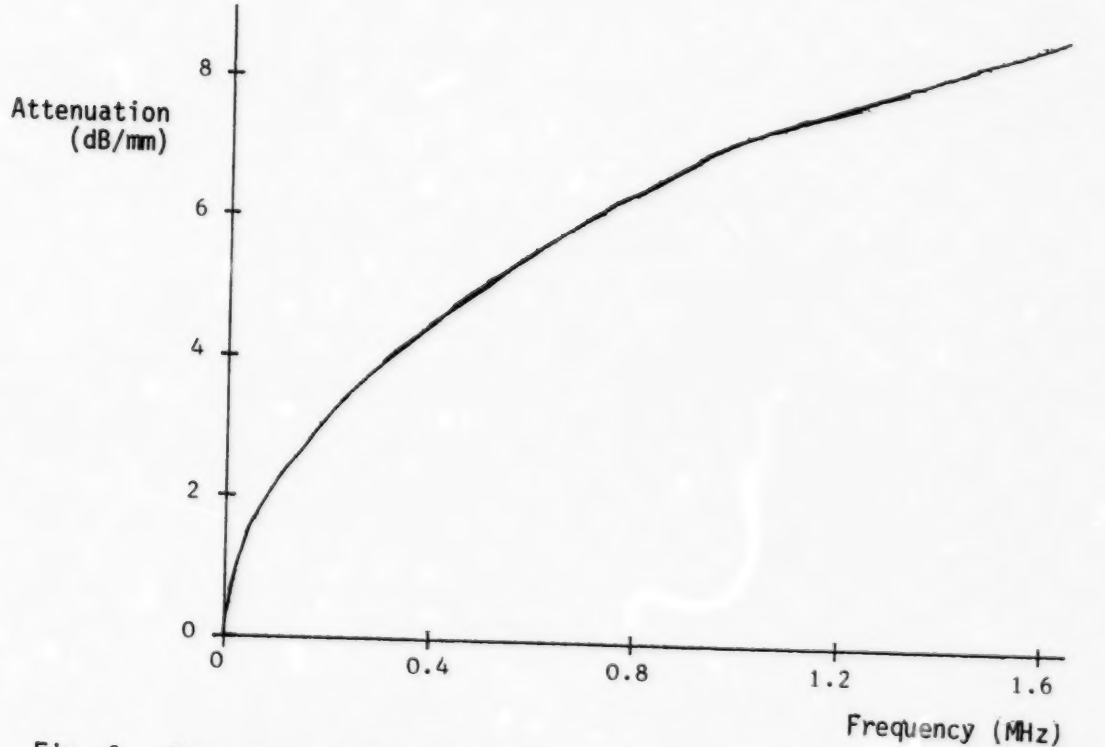

Fig. 6. Shear attenuation versus frequency for oil of viscosity 50 poise.

The principal influence on viscosity for any oil is temperature. Figure 7 shows our own measurements of the viscosity of a sample of Beaufort Sea crude as a function of temperature. From 20°C to 0°C, for instance, the viscosity increases from about 60 to 160 centipoise. At lower temperatures, the fractional rate of change is increasingly rapid. It is reasonable to say, however, that because the oil is in intimate thermal contact with the water it will remain at the temperature of the sea rather than of the air, which not only limits the possible temperature range but makes it reasonably estimable for specific situations.

The variation of viscosity with weathering time has been reported extensively by Suzuki and Miki (1984), in a study of oil skimmers. This variation is less severe, but much less predictable, than is temperature variation. The amount of change depends on weathering time, weathering temperature, and slick thickness. Figure 8 shows the variation of viscosity with weathering time at 0°C for various slick thickness, with the viscosities being measured at 20°C and 40°C using a capillary method. In 70 hours, the thinnest slick increased in viscosity by a factor of slightly more than 3. It must be remembered, of course, that this study was for a specific oil (Khafji crude) and the similarity of the weathering behaviour for other crudes is not well known.

Another study, published recently by Buist and Bjerkelund (1986), gives oil viscosity as a function of volume percent evaporated. Their data are shown in Figure 9 for Alberta sweet mixed blend crude oil. For 20% evaporation, the viscosity has increased by almost 1000 times over that at no evaporation loss. Also reported by Buist and Bjerkelund (1986) are figures on slick thickness as a function of time, for 1 m^3 test spills. Generally, thicknesses dropped from a few millimetres to 100 microns, or less, over a few hours.

Finally, a large variation in viscosity can be expected as a result of oil origins and type. Therefore, prior knowledge of oil origin and type in a particular spill situation would be beneficial.

Clearly, any technique for oil thickness measurement using acoustic waves must take into account these substantial variations in oil viscosity. This requirement will mean either designing an instrument sophisticated enough to be self-compensating, or using what is known about a particular spill to calibrate the device at each use. The latter option is not practical and it is preferred to have an instrument that does not require calibration for every particular situation. Therefore, a self-compensating instrument appears to be the only acceptable alternative.

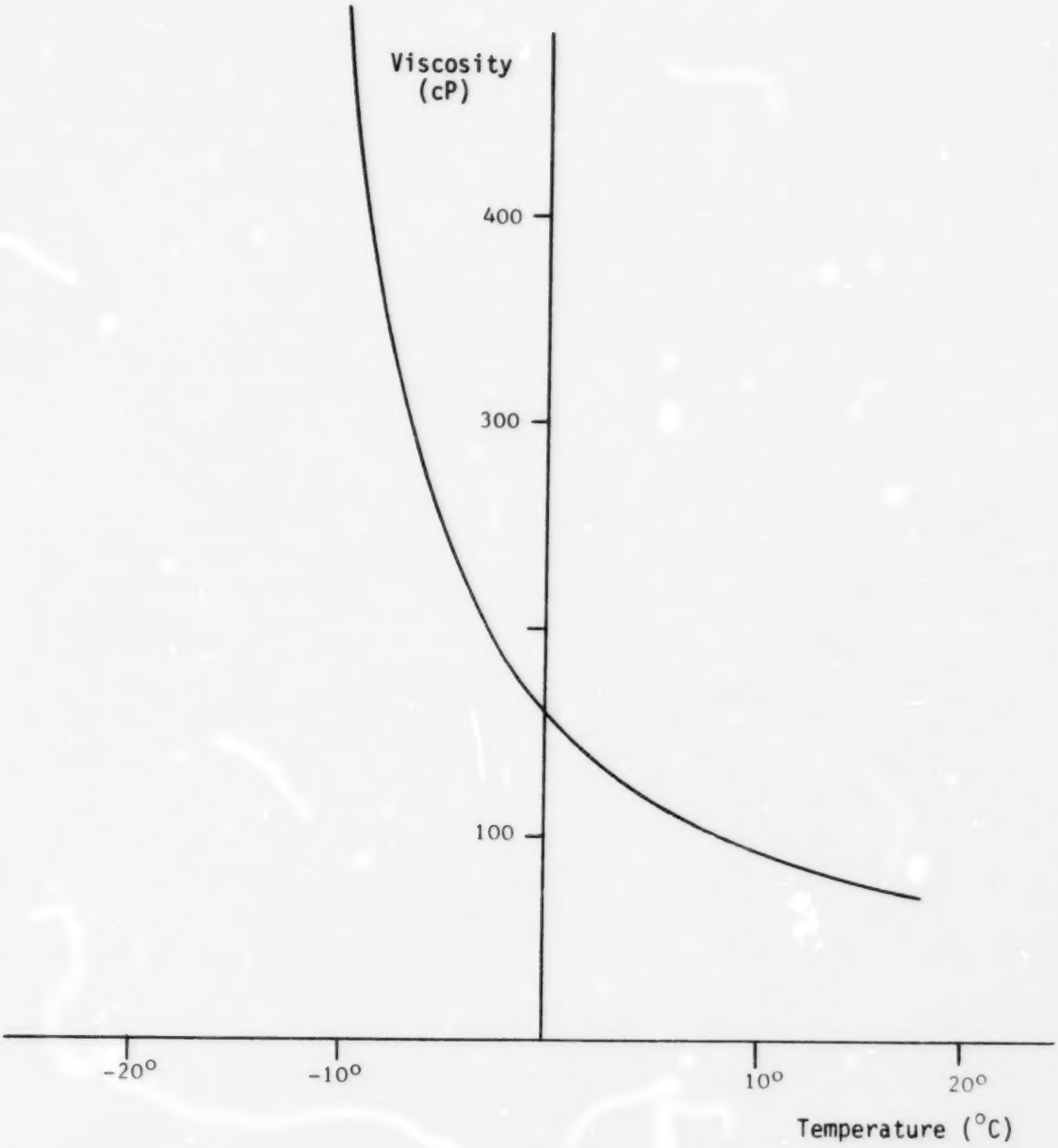

Fig. 7. Viscosity of Beaufort Sea crude oil versus temperature, measured using Brookfield spindle viscometer.

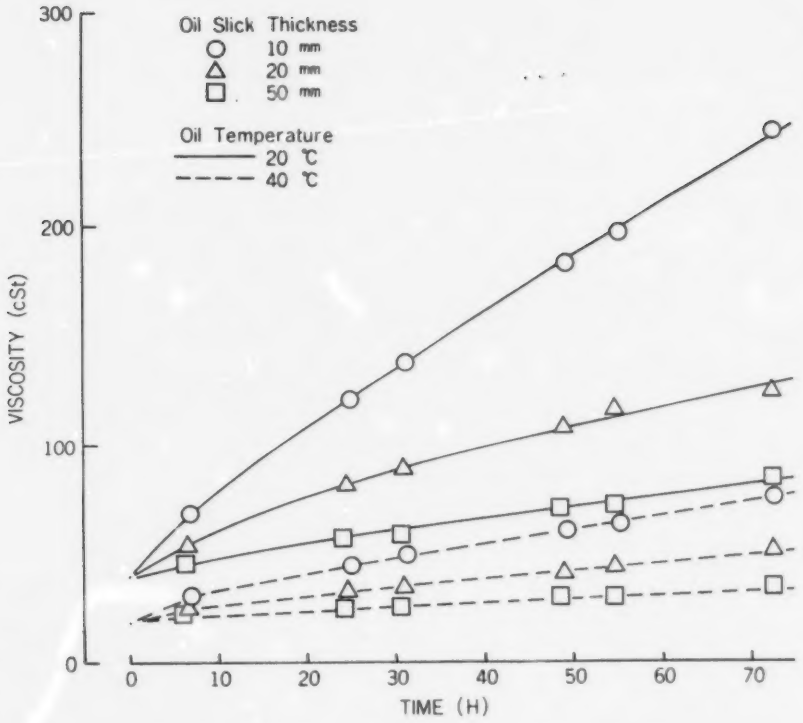

Fig. 8. Viscosity of Khafji crude oil versus weathering time at 0°C (from Suzuki and Miki 1984).

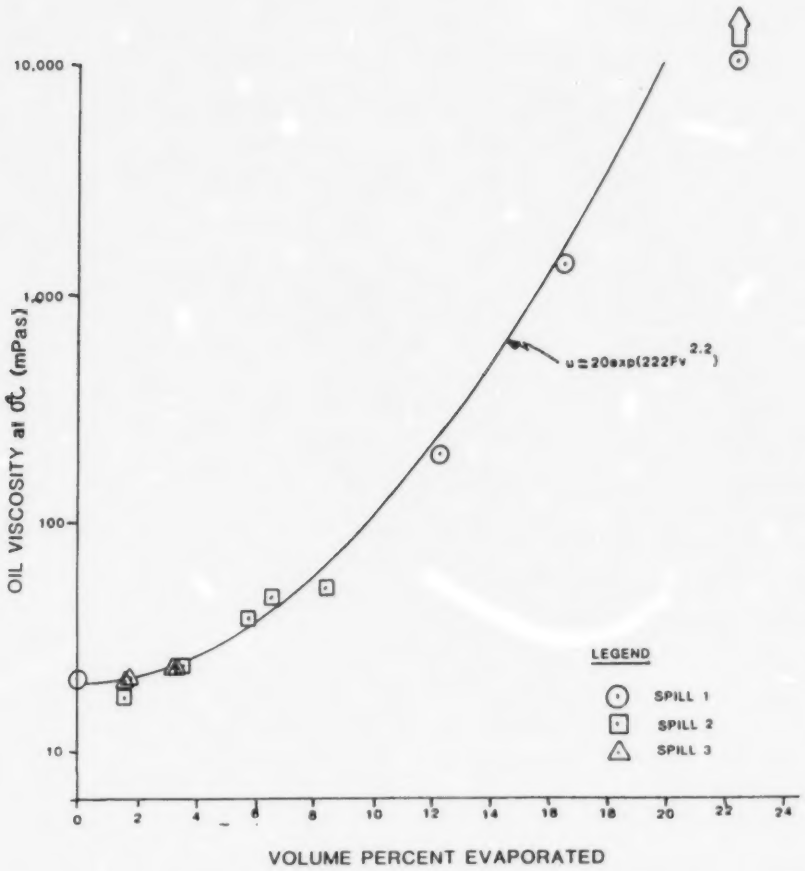

Fig. 9. Oil viscosity versus evaporation (from Buist and Bjerkelund 1986).

RAYLEIGH WAVES

The complexity of the study of acoustic waves in elastic or visco-elastic materials, as opposed to fluids, results in large part from the existence of shear waves, in which the particle motion is perpendicular to the wave propagation direction, in addition to the compressional waves that occur in all media. In general, the effect of a material boundary will be to couple these two modes of acoustic propagation, so that mode conversion effects take place. At a plane boundary between an elastic solid and a vacuum or gas, the coupling provided by the surface makes possible a wave that is essentially bound to the surface, and thus propagates in a two-dimensional, rather than a three-dimensional, space. These waves were originally predicted by J. Strutt (Lord Rayleigh) more than 100 years ago. They are also called surface acoustic waves (SAW) and have, in recent years, found major applications in signal processing devices, non-destructive testing, and other areas.

The displacements involved in surface waves are clearly illustrated in Figure 10. The amplitudes of the particle velocities and displacements decay rapidly with depth into the medium, and there is no energy transmission in this direction. Because the wave is a coupled one, the attenuation will result from the loss mechanisms for both compressional and shear waves. The velocity of propagation of the Rayleigh wave usually lies between 0.87 and 0.96 times the shear wave velocity (Ristic 1983), the exact relationship being a function of Poisson's ratio for the material. In special cases the Rayleigh velocity will exceed the shear velocity; in these instances the wave will continuously "leak" energy into the interior of the solid. Such waves are frequently called "leaky Rayleigh waves."

When the medium carrying the Rayleigh waves is a visco-elastic substance rather than an elastic solid, the shear characteristics are highly dependent on frequency. For this reason the velocity and attenuation of the Rayleigh wave will also exhibit a high degree of frequency dependence. At frequencies far above the relaxation frequency for the material, the behaviour will be much as for a wholly elastic medium, but for lower frequencies the velocity can be expected to drop quite rapidly, and hence, the wavelength will not increase as quickly as would otherwise be expected.

The usual extent of a Rayleigh wave into the medium is about one Rayleigh wavelength (Figure 11). Thus, the thickness of the medium will be of essentially no consequence as long as it exceeds a few wavelengths. If the thickness becomes less than this, or the wavelength is increased by decreasing the wave frequency, then the second boundary will start to influence the wave. In this case we move into the region of plate or Lamb waves, which are discussed later. The important fact is that these waves have somewhat different propagational characteristics. Thus, a reasonable approach to determining the thickness of some layer would be to generate Rayleigh waves on its surface, and to lower the frequency until the onset of plate oscillations was detected. By using broad-band transducers and electronics, a wide range of thicknesses could be interrogated in this way.

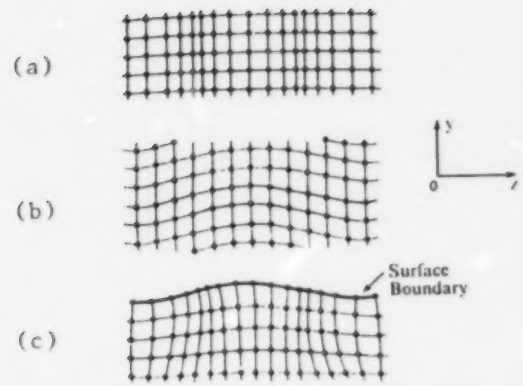

Fig. 10. Displacement patterns for (a) compressional wave, (b) y-polarized shear wave, and (c) Rayleigh wave, all propagating in the z direction (from Ristic 1983).

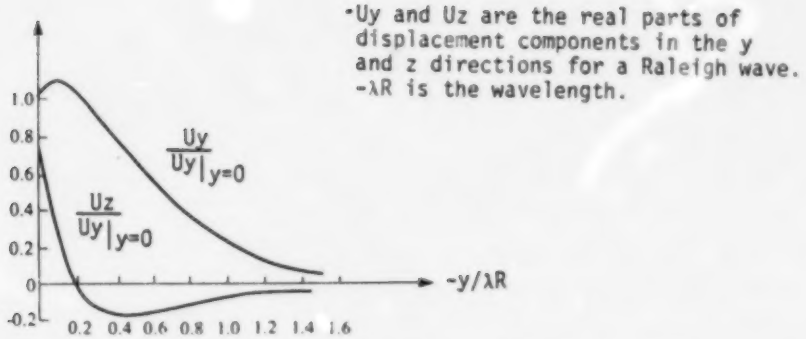

Fig. 11. Typical normalized displacements for a Rayleigh wave (from Ristic 1983).

The difficulty with using such a technique in a visco-elastic material such as oil is that as the frequency is varied, there are two competing effects: the variation in effective thickness of the layer (in wavelengths) and the changes in shear properties of the medium. As the frequency is lowered, oil behaves more and more like a liquid in terms of its shear response. This behaviour creates two problems. First, if the propagational velocity drops quickly as the frequency is decreased then it might be difficult to achieve, at reasonable operating frequencies, wavelengths sufficient for interrogating other than the thinnest of oil layers. Secondly, the rapid attenuation for all but the highest frequencies could make transmission and detection of the waves exceedingly difficult.

Certainly if such factors should show this straightforward measurement technique to be unfeasible, there are other less-direct methods available for investigating oil thickness, which are discussed later under Other Acoustical Methods. However, a proper assessment of the initially proposed method first required specific information on the shear properties of oil for the circumstances of interest. This information has been obtained, and has already been discussed.

The velocity of Rayleigh waves can be determined from the shear and compressional velocities, using the expression:

$$\frac{V_R}{V_S} = \frac{0.87 + 1.12\sigma}{1 + \sigma} . \qquad (9)$$

Here V_R and V_S are the Rayleigh and shear velocities respectively, and σ is the Poisson's ratio. This equation is empirical, but is estimated to be accurate to better than 0.5% in most cases. Poisson's ratio is not constant for visco-elastic materials, but is a function of shear velocity, according to:

$$\sigma = \frac{1 - 2(V_S/V_1)^2}{2(1 - (V_S/V_1)^2)} \qquad (10)$$

where V_1 is the compressional velocity in the oil.

Using equations 9 and 10, the velocity of Rayleigh waves and the wavelength as a function of frequency were calculated. The results are given in Figures 12 and 13. Because the attenuation of compressional waves in oil is far less than that of shear waves, the Rayleigh attenuation will be about equal to the shear attenuation. Using this approximation, we now have numerical data on all the propagational characteristics of Rayleigh waves on the surface of crude oil, as functions of frequency.

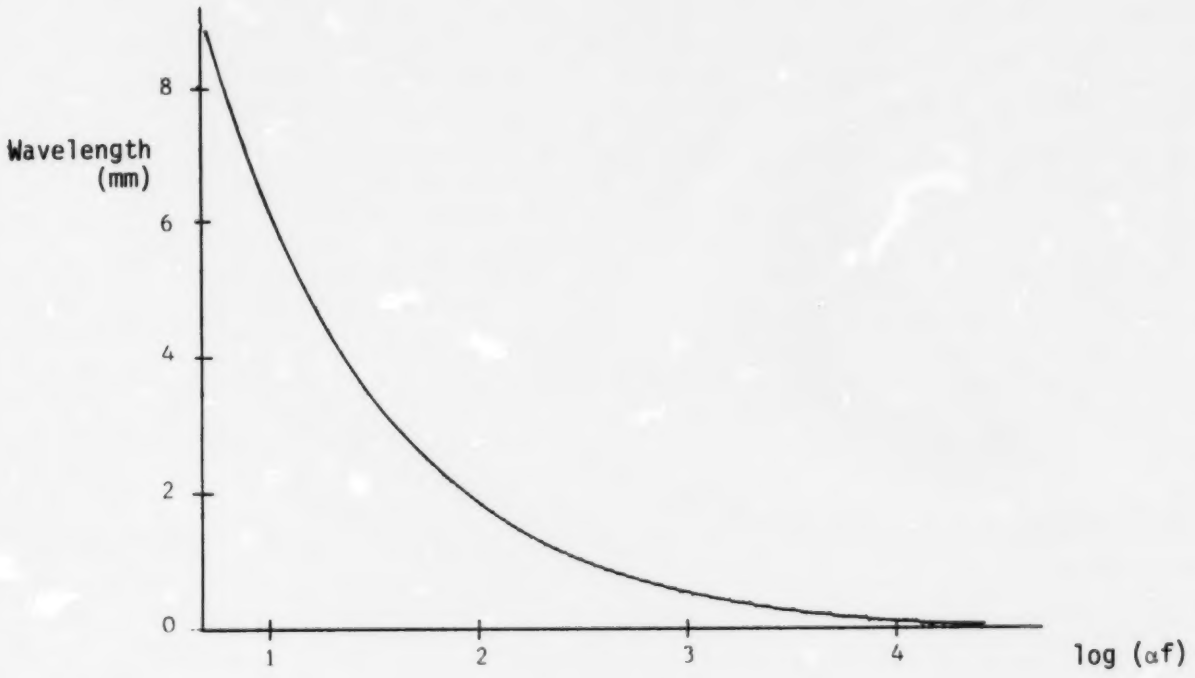

Fig. 12. Rayleigh wavelength in crude oil versus frequency.

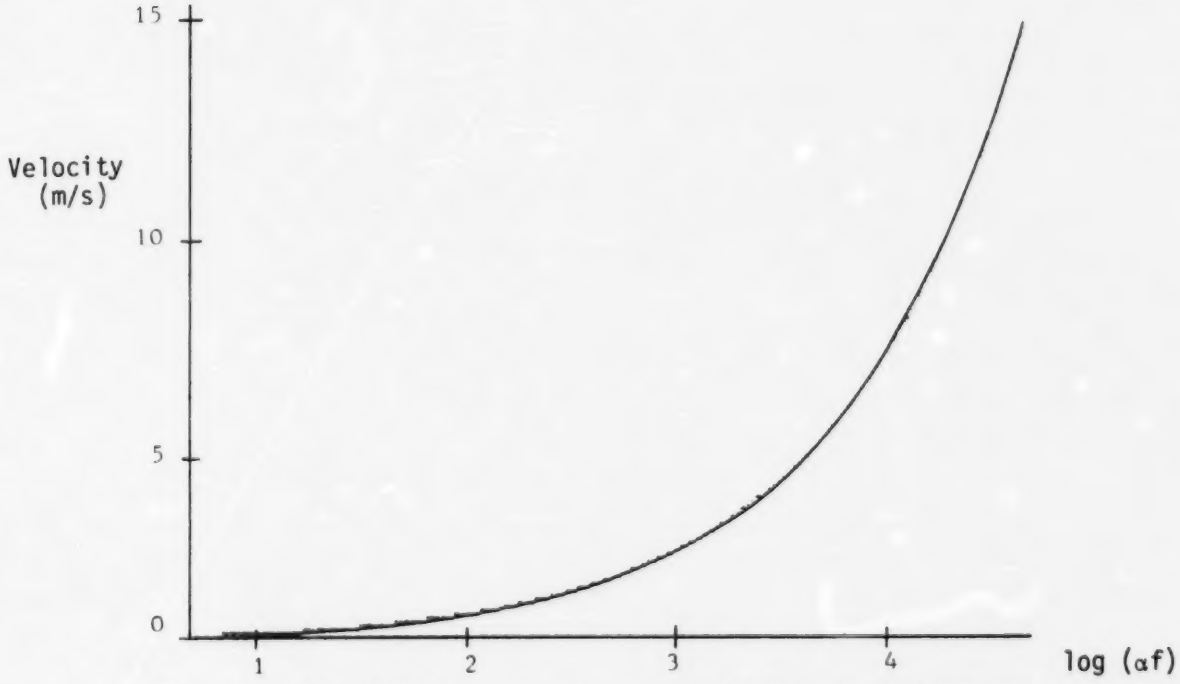

Fig. 13. Rayleigh wave velocity in crude oil versus frequency.

Figure 12 shows that the wavelengths required are realizable, but at rather low frequencies. For instance, the wavelength at 1 KHz is only about 2 mm. Because most SAW devices operate in the MHz range, it may prove difficult to couple transducers with the oil for such low frequencies under 100 KHz. This point should be explored experimentally as the literature shows no adequate theoretical grounds on which to make a precise analysis of transduction efficiency.

Initial experimental measurements might show the shear velocities to be higher than those predicted, if the heavier components of the oil can have independent shear vibration modes, as suggested in the oil properties section. If this is the case, then the frequency operating range required would be more convenient. If not, however, it would be necessary to examine the generation and detection of Rayleigh waves from about 1 MHz down to below 1 KHz if possible.

The attenuation values with frequency are very substantial, for instance, about 80 dB/cm at 100 KHz, as a result of the small wavelengths predicted by the extrapolated oil data. Although this attenuation will make detection difficult at the higher frequencies, it does not make the technique unfeasible. If the wavelength predictions are accurate, then operation would be at lower frequencies than 100 KHz for all but the thinnest oil layers (10 to 100 microns). Again, the wide relaxation spectrum of the oil might result in longer wavelengths, as discussed earlier, which would substantially reduce the attenuation. If this is the case, Rayleigh waves would be far more readily detectable.

LAMB WAVES

Lamb waves, like Rayleigh waves, consist of a coupled longitudinal and shear motion. However, they are plate-type disturbances rather than surface modes. Plate waves are modes of vibration of a layer in which the entire thickness of the medium is disturbed, and they generally exist for a range of wavelengths greater than the thickness of the layer involved. For wavelengths shorter than this, their characteristics begin to shift, approaching closer and closer to those of surface waves.

In spite of the dichotomy between surface and plate modes of vibration, Rayleigh and Lamb waves may be considered to be special cases of a more general wave type. As already stated, the propagation characteristics (as described by the dispersion relations) of the two waves change continuously from one to the other as the ratio of the thickness of the medium to the wavelength of the wave is varied from (ideally) infinity to much less than one. A Lamb wave, however, may be regarded as a superposition of two Rayleigh-type waves, one associated with each of the surfaces of a layer. Conversely, a Rayleigh wave on one surface may be treated as the sum of two Lamb waves.

One fundamental difference between the two wave types is that only one Rayleigh mode exists, whereas many Lamb modes are possible. A mode is characterized by a particular pattern of behaviour of the amplitude of the wave as a function of depth into the medium. Furthermore, these modes may be classified into two types; those in which the amplitude of the wave motion as a function of depth is symmetric around the centre-line of the plate, and those in which the amplitude function is asymmetric. The displacement patterns for the first three symmetric and asymmetric modes, as reported by Auld (1973), are shown in Figure 14. Higher modes may also be considered.

The characteristics of Lamb waves are arrived at using a method known as transverse resonance analysis. This technique mathematically decomposes the plate wave into a compressional and a shear wave, both of which are reflected back and forth between the boundaries of the plate. These partial waves are illustrated in Figure 15. The plate thus acts as a wave guide confining the propagation of the disturbance. The components of the two wave vectors in the direction of propagation must be equal by definition to satisfy the condition of coupling between the wave components. The analysis proceeds by a consideration of the reflection coefficients for the surfaces, leading to the Rayleigh-Lamb frequency equations:

$$\frac{\tan k_{ts} b/2}{\tan k_{t1} b/2} = \frac{-4\beta^2 k_{t1} k_{ts}}{(k_{ts}^2 - k_{t1}^2)^2} \qquad (11)$$

for the symmetric modes and

$$\frac{\tan k_{ts} b/2}{\tan k_{t1} b/2} = \frac{-(k_{ts}^2 - k_{t1}^2)^2}{4\beta^2 k_{t1} k_{ts}} \qquad (12)$$

for the asymmetric modes, where k_{ts} and k_{t1} are the transverse components of the shear and compressional partial wave vectors, respectively; β is the component of both wave vectors in the direction of propagation, referred to as the propagation wave number, or propagation factor, and b is the thickness of the medium. These quantities are related to the angular frequency of the wave, ω, as follows:

$$k_{t1}^2 = (\omega/V_1)^2 - \beta^2 \qquad (13)$$

$$k_{ts}^2 = (\omega/V_s)^2 - \beta^2 \qquad (14)$$

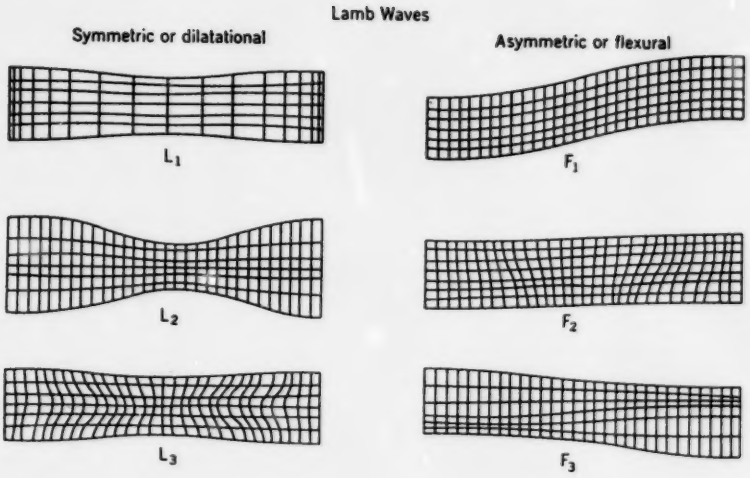

Fig. 14. Displacement patterns for the first three symmetric and asymmetric Lamb wave modes (from Auld 1973).

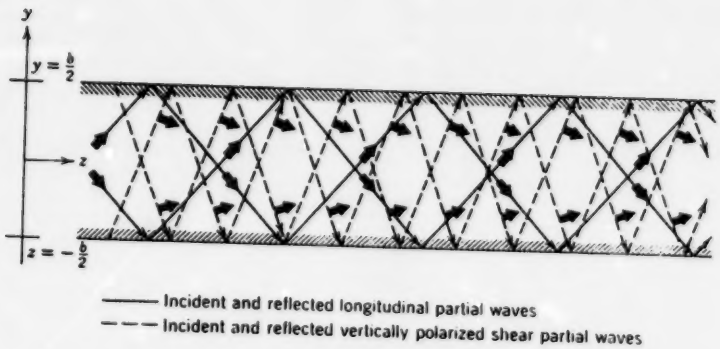

Fig. 15. Partial wave patterns for transverse resonance analysis of Lamb waves in a free layer (from Auld 1973).

where V_l and V_s are the velocities of the compressional and shear waves in the medium. In the case of oil, V_s is actually a function of the frequency.

Equations 11 and 14 may be solved simultaneously for ω as a function of β. The propagation characteristics are thus completely determined, because the phase and group velocities, V and V_g, are related to these quantities by

$$V = \omega/\beta \tag{15}$$

$$V_g = d\omega/d\beta \tag{16}$$

and the wavelength, λ, is simply

$$\lambda = 2\pi/\beta \tag{17}$$

The phase velocity is the velocity of a monochromatic wave of a given frequency, that is, a wave with no frequency components other than the specified one. The group velocity, on the other hand, is the velocity of propagation of a wave "packet" that may be broken down into more than one component, each with a different frequency.

Equations 11 to 14 are transcendental, that is, they cannot be solved by any explicit mathematical technique. It is therefore necessary to solve them numerically using a computer, a task made rather difficult by the presence of numerous discontinuities. The results for a typical Lamb mode for oil thicknesses of 10 microns, 100 microns, 1 mm, and 1 cm are given in Figures 16 to 19. The shear velocity as a function of frequency, required for the solution of the equations, was derived from empirical data giving the shear mechanical impedance of the oil, as described earlier.

In all four cases, there is a sudden change in the velocity curve in the vicinity where the wavelength is equal to the thickness of the oil layer. This change is significant enough to be detected using methods currently available; however, some difficulty may be encountered because the nature of the transition varies widely with the layer thickness.

The containment of energy in a Lamb mode depends on the reflection characteristics of the interface, as determined by the properties of the media involved. Only those modes for which the angles between the wave vectors of the partial waves and the normal to the boundaries are greater than a certain critical angle, determined by the interface properties, can exist unperturbed by the medium surrounding the plate.

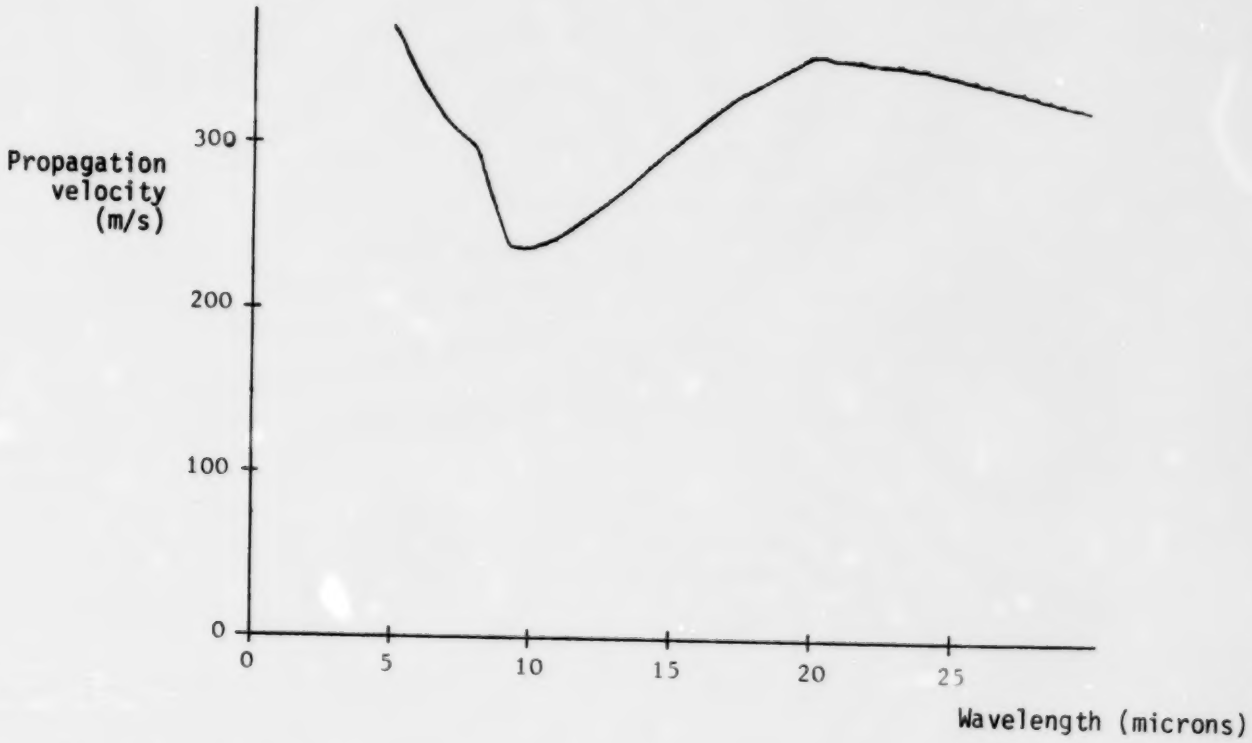

Fig. 16. Propagation of velocity of Lamb waves versus wavelength for an oil thickness of 10 microns.

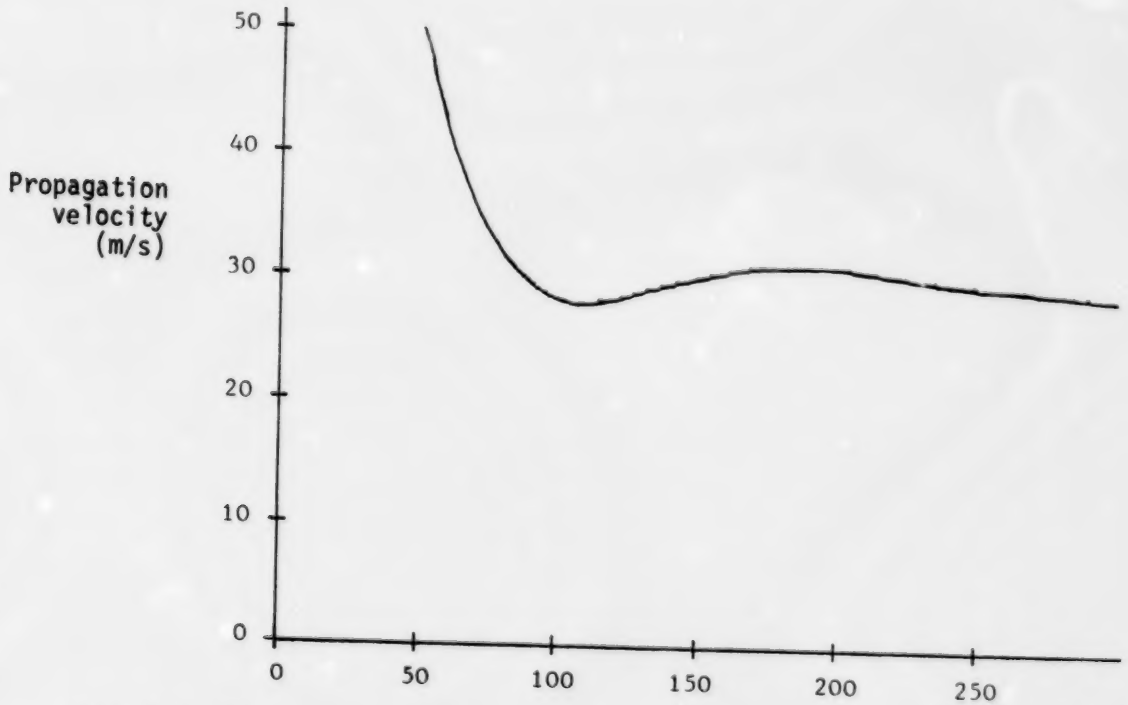

Fig. 17. Propagation of velocity of Lamb waves versus wavelength for an oil thickness of 100 microns.

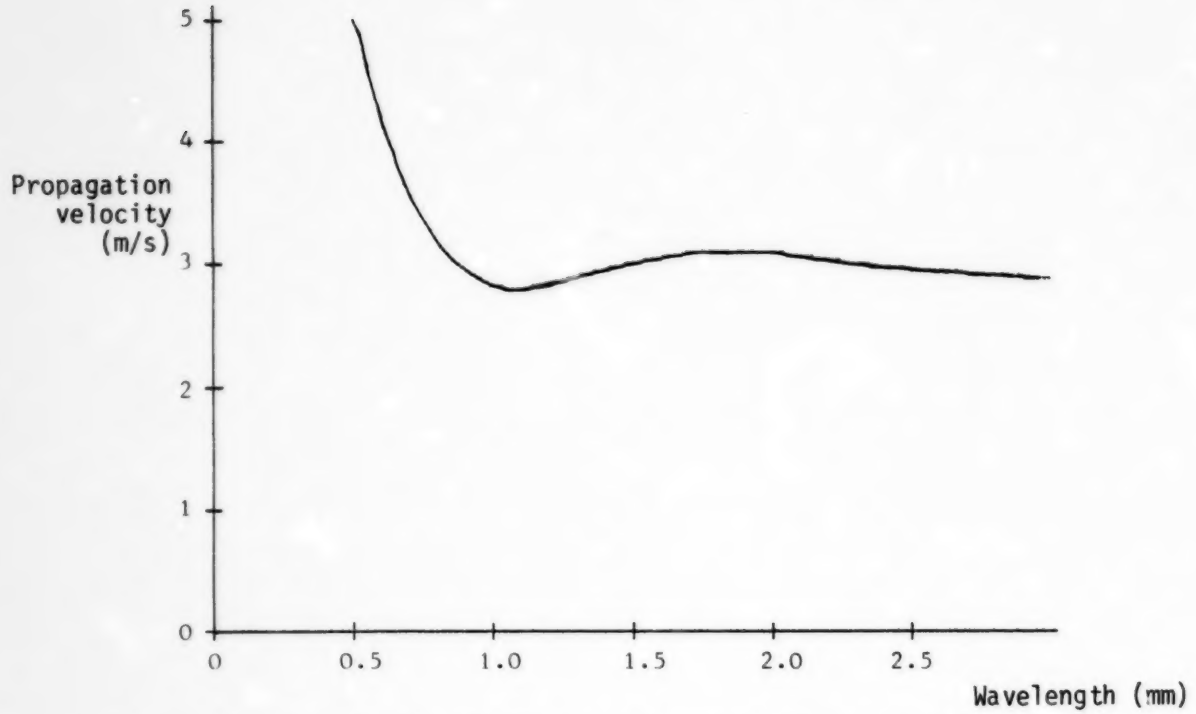

Fig. 18. Propagation velocity of Lamb waves versus wavelength for an oil thickness of 1 mm.

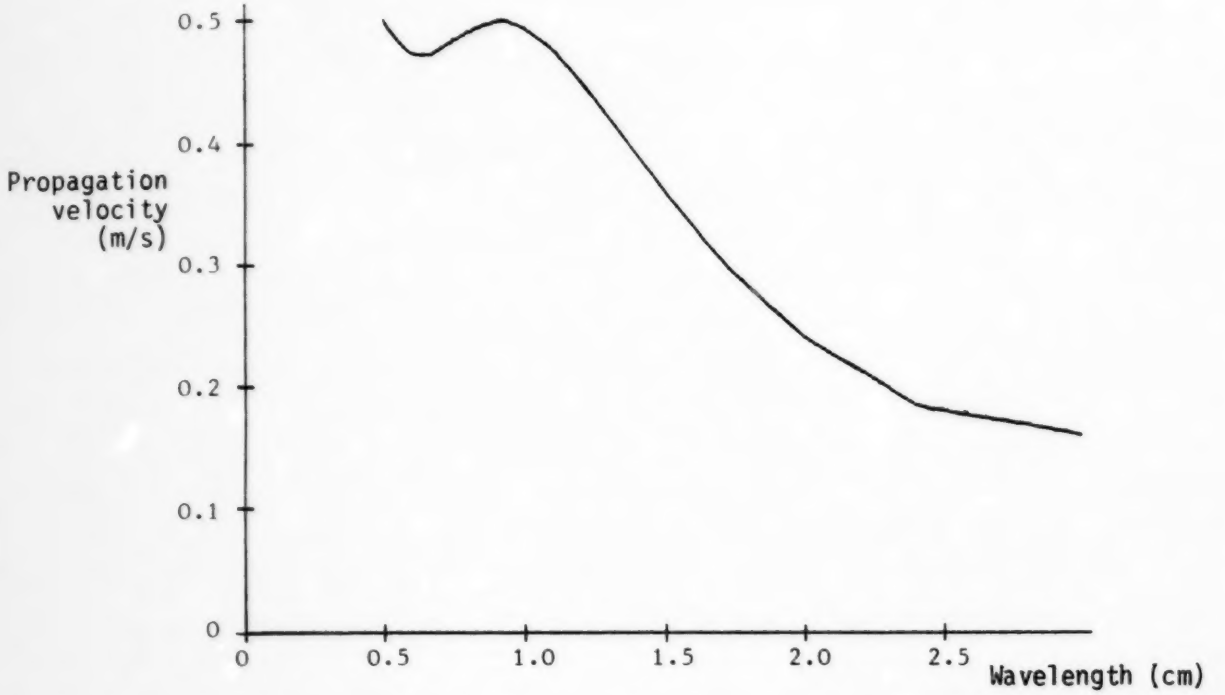

Fig. 19. Propagation velocity of Lamb waves versus wavelength for an oil thickness of 1 cm.

All other modes constitute leaky Lamb waves, which, like leaky Rayleigh waves, radiate energy continuously into the loading medium. In terms of the transverse resonance technique already described, the mechanism by which this occurs can be regarded as being the generation of radiating waves in the loading medium via mode conversion of the partial waves at the interface, as illustrated in Figure 20. The more similar are the properties of the two media, the closer the critical angle becomes to 90°, and the more rapidly the leaky waves loses energy, making them more and more difficult to propagate. Such a high critical angle makes it extremely difficult to generate freely propagating (non-leaky) waves, as will become apparent on perusal of the section on Generation and Detection of Coupled Waves.

The properties of oil and water with respect to compressional waves are similar. Measurements have shown that the relevant velocities in the two media are within a few percent of each other. Thus, in the case of an oil layer loaded by water on one boundary, it is unlikely that Lamb waves could be confined to, and propagated in, the layer for any reasonable distance. This fact, however, could have a positive effect on the problem under consideration, the determination of oil layer thickness, by returning the situation to the ideal case originally hypothesized, in which there is a sharp cutoff wavelength (and hence, corresponding frequency) below which waves will propagate, and above which they will not.

Therefore, it may be hypothesized that although the wavelength is in the Rayleigh regime its energy is confined to a thin region close to the air-oil interface. Only a negligible amount of leakage occurs at this boundary, loading by the air should be negligible because of its low compressional elasticity, and thus its comparatively low tendency to propagate acoustic disturbances. As the wavelength increases, the disturbance penetrates deeper into the layer, approaching closer to the oil-water interface. The wave thus approaches the Lamb regime. The proximity of the disturbance to the interface with the water makes it possible for energy to begin to leak out. This effect increases more and more rapidly with wavelength, resulting in quite a distinct cutoff point that should be readily detectable.

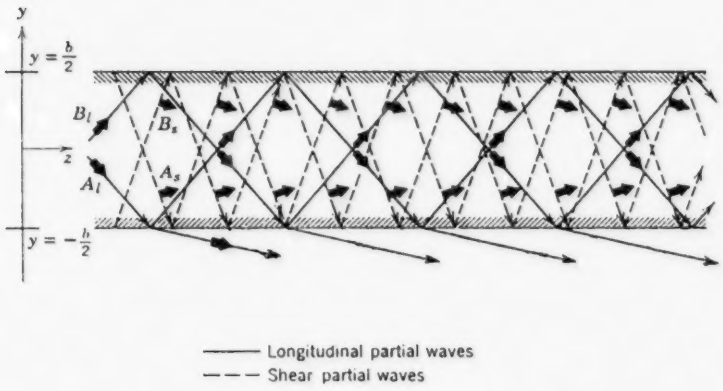

Fig. 20. Partial wave patterns for transverse resonance analysis of Lamb waves, in a layer bounded on one side by a water half-space (adapted from Auld 1973).

GENERATION AND DETECTION OF COUPLED WAVES

The valuable practical applications of surface acoustic waves have necessitated the refinement of techniques for generating the waves relatively efficiently. Any such method must be capable of producing both shear and compressional acoustic excitations, either directly or indirectly. These two components are then coupled by the medium and its geometry, resulting in a surface acoustic wave.

There are two basic methods by which the excitation of SAWs have been achieved. The first of these, discussed by Ristic (1983), employs direct generation of both the shear and compressional components of the wave. This process involves the use of a transducer that converts an electrical signal into a mechanical force. This force then causes a periodic displacement that propagates an acoustic wave. The force may be generated in a number of ways. In the case of nonpiezoelectric media, the simplest method that might be used involves the Lorentz force. This is the force exerted on a current or current-carrying conductor by a magnetic field.

In the case of a solid, nonpiezoelectric medium, a meander-conductive pattern is deposited onto the substrate, as shown in Figure 21. A constant-bias magnetic field is applied to the system in the plane containing the displacements, at some angle (measured from the surface of the medium) chosen so as to achieve maximum transducer efficiency. An alternating current is then passed through the conductor, causing a corresponding force of the same frequency to be exerted on the conductor by the magnetic field. The force then generates the desired components of motion. Theoretical and experimental results have shown that maximum transduction efficiency occurs when the biasing magnetic field is perpendicular to the substrate surface. Acoustic coupling between the conductor and a solid substrate is achieved by virtue of the fact that the two are physically attached.

The second basic method by which SAWs may be produced is to generate a compressional wave in a separate medium, usually in the form of a wedge or prism (though in some cases the medium may be of large or infinite extent, and the compressional wave simply a beam within it), and to then rely on mode conversion at the interface between this medium and that in which the SAW is desired, as shown in Figure 22. This technique is far less complex than the first, described above, in that it requires the direct generation of only a compressional wave, which need not be elaborated here. The underlying principle behind the method is that, in general, when a compressional wave strikes the boundary of a medium that supports shear waves, it scatters into two resultant waves - one compressional and one shear. If the incident wave strikes the boundary at a certain specific angle, the two scattered waves would be coupled together to form a surface wave. The necessary angle is determined by the requirement that the components of the wave vectors of the two waves in the direction of propagation must be equal.

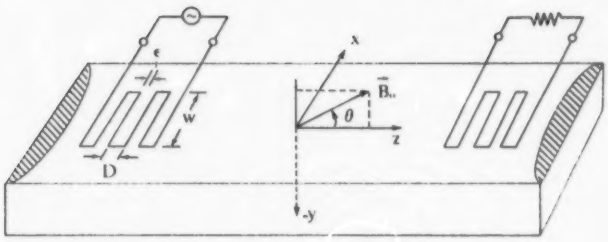

Fig. 21. Excitation of surface acoustic waves on a solid substrate (from Ristic 1983).

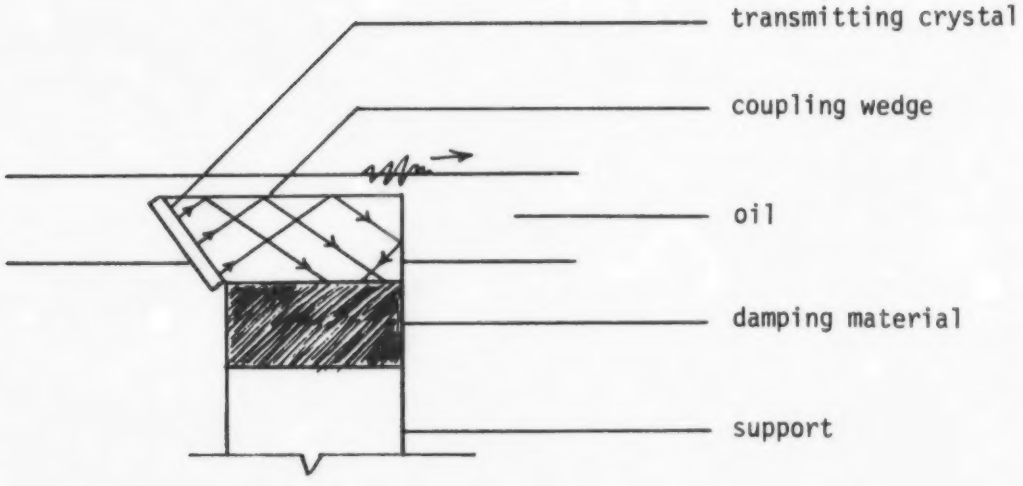

Fig. 22. The generation of SAWs using a compressional wave/wedge technique.

The generation of plate vibrations may be effected in a manner similar to that used for surface disturbances - both types of waves consist of coupled longitudinal and transverse motions. The difference in the case of plate modes is that both boundaries participate in the coupling, thereby changing the properties of the resultant wave. The existence of two boundaries also requires that consideration be given to the fact that scattered waves will now be produced at each interface. It therefore becomes necessary to ensure that the two pairs do not interface in an undesirable manner.

A practical apparatus would have to be capable of operation over a wide range of frequencies. The technique of a compressional-wave excitation would necessitate the use either of a broad band transducer (such as a tapered one) capable of excitation over the required frequency range, or of more than one transducer (possibly two or three), each capable of operation in a particular sub-range of frequencies. Access to a wide frequency range can also be achieved in the case of direct generation techniques by varying the frequency of the electrical excitation signal.

Detection of the waves produced could be accomplished using a SAW transducer similar to the type used for direct generation, or by using a compressional transducer to pick up the longitudinal component of the disturbance. The detection transducer would, of course, also have to have a good response in the frequency range of interest.

For successful detection and identification of the Rayleigh waves to take place, it is necessary to be able to distinguish them from other acoustic modes. The most significant restriction imposed by this requirement is that the receiving transducer must be well outside the beam angle of the generating transducer (if a free beam is used) in the case of the compressional generation technique, to avoid confusion between the excitation beam and the surface waves. Thus, the SAWs are required to propagate the distance demanded by this condition and still be of sufficient amplitude to be detectable. A further restriction on the distance of propagation required is the possibility of interference of the detection transducer with the source, or point of generation, of the Rayleigh waves on the oil surface.

Another factor that must be taken into account is the effect of the transducers on the thickness of the oil layer. The oil will naturally creep up the sides of any objects present, increasing the layer thickness at these points. However, assuming that the transducers are at least a few millimetres apart, a significant portion of the path of the surface waves will be through a part of the layer having a thickness equal to the unperturbed value. Because the maximum wavelength is the parameter of interest, oil creep induced by the presence of the transducers is not expected to have any significant effect on the determination of layer thickness.

PILOT EXPERIMENT

A pilot experiment was carried out in an attempt to generate Rayleigh waves in oil by taking advantage of the visco-elastic properties of the oil, and then to establish the dependence of propagation characteristics on oil layer thickness. In this way the feasibility of a frequency-based, acoustic, thickness measurement could be assessed. It should be stated that the present pilot experiment was only intended to be an initial, limited-scale, experimental study to determine whether more comprehensive experiments were justified. For this reason, no attempt was made for special instrumentation or construction of special transducers. The experimental set-up, test procedure, and results are described in the following paragraphs.

Surface acoustic waves have wide application in areas such as non-destructive testing and signal-processing devices. But in all these cases they are generated and propagated on solid substrates. No information is available in the literature on Rayleigh waves in visco-elastic media, which means that for the purposes of this work it is not possible to use an existing device with straightforward modifications. In particular, entirely new transduction techniques must be established. The two main types of transducers used to generate SAW on solids are coupling wedges and interstitial finger transducers. The finger transducers require a piezoelectric substrate, so they cannot be used on oil. The wedge technique also has a major difficulty in that a material is required for the wedge that has a compressional velocity less than the shear velocity in the host medium (oil). No liquids or solids satisfy these requirements, and gases have such low acoustic impedances that coupling would be poor. Development of a wedge would require use of a two-phase material, such as expanded plastic. Even if a suitable material could be produced, the wedge would require the shear velocity in oil to be constant and precisely known; theoretical considerations have shown that these requirements are unlikely to be satisfied.

The transduction technique chosen for the experiments involved mode-conversion of an acoustic compressional wave into Rayleigh waves at a surface-breaking discontinuity. Studies in ultrasonic non-destructive testing have shown that Rayleigh waves are produced when compressional waves strike cracks in the surface, and a study by Saffari and Bond (1986), has considered the mode-conversion for step and slot discontinuities of various sizes in steel. It was decided to produce a discontinuity in the oil by dipping a thin metal strip through the surface, and then to project compressional waves at the strip from below the oil using a hydrophone at the desired frequency, as shown in Figure 23.

This technique has several advantages. Because it is broad-band, it does not require precise knowledge of the Rayleigh wave velocity in the oil. Because only the discontinuity strip touches the oil, interference of the apparatus with the oil thickness is quite low. Finally, the main transducer is a simple hydrophone; a standard, readily available instrument.

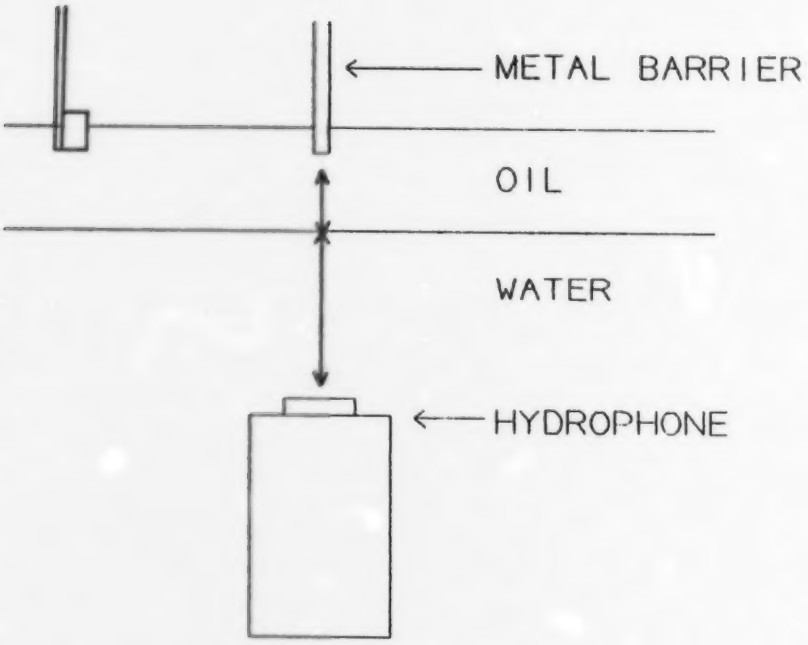

Fig. 23. Experimental set-up with a straight barrier.

It should be borne in mind that there is no clear precedent for the generation and detection of surface and plate waves in oil. Therefore, the attempts in this direction were exploratory.

The test procedure used direct and indirect detection methods. The first method involved attempting to receive a Rayleigh wave directly by using a small transducer placed close to the discontinuity. By using a pulsed technique, time-of-flight could be used to discriminate between a Rayleigh wave and other signals such as reflected compressional waves. The second method was to receive the signal reflected back to the transmitter, and to measure the reduction in signal level when the discontinuity was inserted. Therefore, the loss of energy to the Rayleigh mode could be detected.

For these tests a motor oil of fairly high viscosity was used (50 wt) to reduce the attenuation of Rayleigh waves that might be produced. When the direct detection technique was tested, Rayleigh waves could not be discerned. The system gain was about 90 dB, with 40 dB being accounted for by the transmission and reception efficiency, so that if any Rayleigh waves were present, they were at least 50 dB below the level of the incident compressional wave. This figure would include both the conversion efficiency and the attenuation. From research with slots in steel, Saffari and Bond (1986), reported conversion coefficients from 0.15 to more than 0.5; however the values for the oil case could be lower.

For the indirect detection technique, a 500-KHz transducer was used both to transmit and to receive the pulsed signal. The amplitude of the reflected signal was measured for four cases; water only with or without discontinuity, and oil on water with or without discontinuity. For the water case, addition of the metal strip had little effect on the received signal, but for the oil case, addition of the strip discontinuity caused a substantial reduction in the received signal (about 40%). The results of this experiment are summarized in Table 1. This result was very encouraging, as it meant that oil could be detected clearly, with straightforward simple apparatus and without the requirement of any precise measurements or physical alignments.

TABLE 1

Experimental results of Rayleigh wave detection

Medium	Barrier	Relative Amplitude
Water	No	5.4
	Yes	5.0
Oil and water	No	5.0
	Yes	3.4

The determination of a frequency threshold for this effect was not attempted and was deemed to be beyond the scope of a pilot experiment. However, several difficulties may be noted so that they can be considered during the planning of future experiments. First, no broad-band transducers were available, so that a different transducer was needed for every frequency. The poor directionality of transducers operating at frequencies less than the initial one meant that the received signals were very weak and were almost buried in noise. Adjustment of the oil thickness was even more difficult, because a small amount of oil in a container would not spread out on the water to a uniform thickness, which meant that thin films were difficult to obtain and impossible to measure precisely, given the limited resources available for this initial study.

Because no Rayleigh waves were received directly, it seemed unlikely that the large signal loss observed was entirely the result of mode conversion. Experiments were done with lifting the metal barrier slowly out of the liquid and measuring the change in signal. For both oil and water, a large drop in signal level was observed just before the barrier broke free from the surface. This observation may have been the result of the distortion of the surface shape as the liquid was pulled up with the barrier by surface tension. The distorted surface would reflect less of the incident wave energy back to the hydrophone. The surface tension of water ($\approx$72 dyne/cm) is almost twice as much as that of oil ($\approx$34 dyne/cm) and, hence, the oil surface is expected to be flatter than the water surface at the discontinuity.

When the barrier is removed from the liquid surface, the problem becomes a hydrodynamic one in which viscosity and air-oil surface tension are involved. We were not able to attempt a solution to this problem in the time available but we are not sure that it is directly relevant to the question under study.

An additional test was done with a curved barrier (Figure 24) instead of the flat, thin strip discontinuity used in the previous test. The purpose of the curved surface was to focus Rayleigh waves, if they were produced, to improve their detectability. However, direct detection was not achieved, possibly because of the instrumentation restrictions.

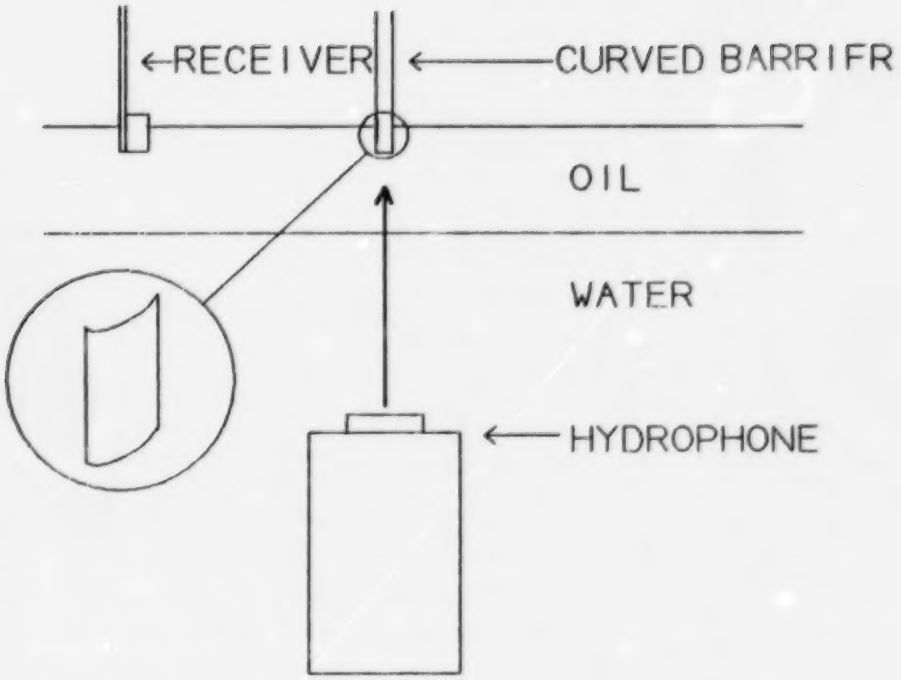

Fig. 24. Experimental set-up with a curved barrier.

OTHER ACOUSTIC METHODS

It has been noted during the discussion of Rayleigh Waves, that there are other acoustical methods that may warrant experimental investigation. The purpose of this section is briefly to introduce these alternative methods. A thorough investigation of these techniques is, however, beyond the scope of this study.

It is possible to excite a surface or Lamb wave in a layer by irradiating it with a compressional wave at some critical angle. The degree of coupling into the layer vibration mode will depend on the relationship between the wavelength and the oil thickness. Thus, a possibility is to direct a continuous compressional wave at the oil from below at some appropriate angle, to sweep the transmitted frequency, and to measure the amplitude of the compressional wave reflected back from the surface. Because this amplitude will depend on the amount of energy lost in the layer, comparison of the amplitude variation with some calibrated curve should yield information on the oil thickness. It may simply be that below a certain frequency the oil layer will not be perceived, as its thickness will be much less than the compressional wavelength.

Another possibility is to actually attempt to measure the critical angle for the coupling already described. This method would require mechanically sweeping the orientation of the compressional transmitter, and so the device would have to be quite complex and probably rather fragile.

It is also possible to employ a pulsed technique using a compressional transmitter in the water below the oil. Such a device would employ the fact that reflection at the oil-air interface would produce both a compressional and a shear wave. The shear pulse would propagate more slowly back through the oil layer, and would then produce a compressional signal at the oil-water interface. Both mode conversion effects would be highly angle-dependent. If the two returning pulses were separable in the time domain, oil thickness could be determined by measuring the delay between the two arrival times. Naturally, a time measurement would require more complex circuitry than an amplitude measurement, which would make the device less attractive as a disposable, single-use instrument because of cost considerations.

FREQUENCY-DEPENDENT TECHNIQUE

APPROACH

To measure oil thickness by this technique, requires an acoustic source able to generate sound over a broad range of frequencies and an acoustic detector. The source creates acoustic waves that impinge upon the oil surface and are reflected back to the detector. The amplitude of the detected sound depends on the coefficient of reflection from the oil layer, and on geometry of the situation. To measure the reflection coefficient as a function of frequency, the source may either scan over the requisite frequency range, generating only one frequency at a time, or generate white noise containing a broad distribution of frequencies. In the former case, the receiver need only measure the reflected amplitude at the same frequency as the source is emitting, allowing filtering of unwanted noise, whereas in the latter case the detector must spectrally analyze the reflected signal. The relative merits of the two techniques depend on the signal-to-noise (S/N) ratio which can be achieved. The "signal" in this case is the frequency-dependent change in amplitude of the reflected acoustic wave. The "noise" is unwanted variations in the measured reflected power caused by external sources of sound, uncalibrated frequency responses of acoustic transmitters and receivers, or inaccuracies in the measurement of the strength of the reflected signal. In the next section, we calculate the anticipated signal, and follow with a discussion of some acoustic generator-receiver combinations that can be used to enhance the S/N ratio.

CALCULATION OF REFLECTION COEFFICIENTS

An illustration of the reflected transmission of acoustic waves incident upon a layer of oil floating on water is presented in Figure 25. An oil layer 1-10 mm thick floats on a deep body of water. An acoustic wave of amplitude E_i is incident from the air onto the surface of the oil. A wave of amplitude $r_{ao}E_i$ is reflected from the surface of the oil, where r_{ao} is the reflection coefficient at the air-oil interface. Another wave of amplitude $t_{ao}E_i$ is transmitted into the oil, where t_{ao} is the air-oil transmission coefficient. This latter wave is split similarly at the oil-water interface. The reflection coefficient there is r_{ow}, resulting in a reflected wave having an amplitude $r_{ow}t_{ao}E_i$. This secondary wave travels through the oil layer and reaches the oil-air interface, where a portion of it, determined by the reflection coefficient r_{oa}, is reflected once again whereas a portion, given by t_{oa}, is transmitted into the air. This transmitted wave interferes with the primary reflection, whereas the reflected wave travels back down to the oil-water interface, repeating the process ad infinitum, until the amplitude of the reflected waves diminishes by attenuation.

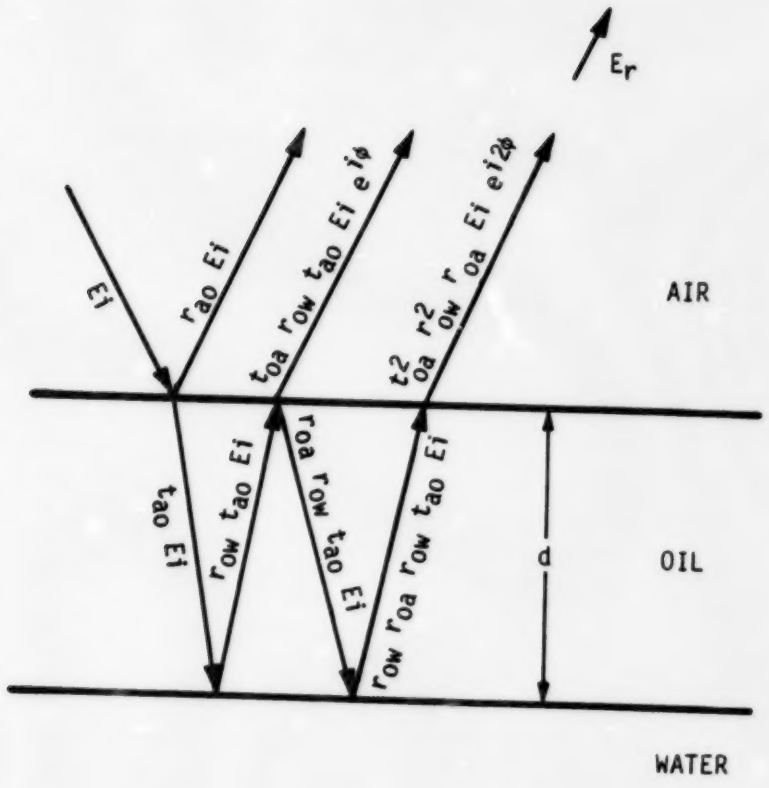

Fig. 25. Illustration of reflection and transmission of acoustic waves incident upon a layer of oil floating on water:

E_i = amplitude of incident acoustic wave
E_r = amplitude of the overall reflection
r_{ao} = reflection coefficient at the air/oil interface
r_{ow} = reflection coefficient at the oil/water interface
t_{ao} = air/oil transmission coefficient
ϕ = phase shift.

The overall reflection coefficient can be calculated by adding the amplitudes of each of the waves that are reflected or transmitted from the oil surface into the air, keeping careful track of the relative phase of each. If the wavelength of the sound in the oil is λ, and the oil thickness is d, then a wave that travels from the top of the oil layer, to the bottom, and back to the top covers a path length 2d. Its phase at the second encounter with the oil-air interface differs by $\phi = 4\pi d/\lambda$ from that at its first encounter. Thus, when adding the amplitudes of the waves reflected into the air, it must be recognized that each subsequent wave is shifted in phase by ϕ from the previous wave. Examination of Figure 25 shows that the amplitude of the overall reflection, E_r, can then be calculated as:

$$E_r = E_i[r_{ao} + r_{ow}t_{ao}t_{oa}e^{i\phi}\{1 + (r_{ow}r_{oa}e^{i\phi}) + (r_{ow}r_{oa}e^{i\phi})^2 + \ldots\}] \tag{18}$$

or

$$E_r = E_i[r_{ao} + (r_{ow}t_{ao}t_{oa})/(e^{-i\phi} - r_{ow}r_{oa})]. \tag{19}$$

Performing the complex algebra shows the overall reflection coefficient, defined as $R = |E_r|/|E_i|$, to be

$$R = \{[-r_{oa} + \frac{r_{ow}t_{ao}t_{oa}(\cos\phi - r_{ow}r_{oa})}{1 - 2r_{ow}r_{oa}\cos\phi + (r_{ow}r_{oa})^2}]^2 + [\frac{r_{ow}t_{ao}t_{oa}\sin\phi}{1 - 2r_{ow}r_{oa}\cos\phi + (r_{ow}r_{oa})^2}]^2\}^{1/2}. \tag{20}$$

The individual reflection and transmission coefficients that enter into this equation may be calculated from acoustic theory (Landau and Lifshitz 1959). Defining z_o, z_a, and z_w as the acoustic impedances of the oil, air, and water respectively, given by the products of their density (ρ_i, where the subscript i may refer to oil, water, or air) and sound speeds (c_i), then the reflection coefficients are given by:

$$r_{ij} = (z_i - z_j) / (z_i + z_j) \tag{21}$$

and the transmission coefficients as

$$t_{ij} = (c_j/c_i)(1 + r_{ij}). \qquad (22)$$

From these equations it is clear that $r_{oa} = -r_{ao}$, and, therefore, that $t_{ao}t_{oa} = 1-(r_{ao})^2$, so that Equation 20 can be written as:

$$R = \{[-r_{oa} + \frac{r_{ow}(1-r_{oa})^2)(c_{os}\ \phi - r_{ow}r_{oa})}{1 - 2r_{ow}r_{oa}\cos\ \phi + (r_{ow}r_{oa})^2}\ ]^2 +$$

$$[\frac{r_{ow}(1-(r_{oa})^2)\sin\ \phi}{1 - 2r_{ow}r_{oa}\cos\ \phi + (r_{ow}r_{oa})^2}]2\}^{1/2}. \qquad (23)$$

Equations 21 and 23 enable calculation of the reflection coefficients when the densities and sound velocities of the three media are known. Both of these quantities are well known for both air and water. For subsequent calculations, we have used the values

$\rho_a = 1.29 \times 10^{-3}$ g/cm^3,

$c_a = 3.31 \times 10^4$ cm/s, and

$c_w = 1.45 \times 10^5$ cm/s, so that

$z_a = 42.8$ g/cm^2/s and

$z_w = 1.45 \times 10^5$ g/cm^2/s.

The speed of sound in oil, and thus the acoustic impedance, varies with the type and age of oil. For the purpose of calculating an example of the variation of the overall reflection coefficient with frequency, typical values of $\rho_o = 0.9$ g/cm^3 (which varies only slightly with oil type and age) and $c_o = 4.2 \times 10^4$ cm/s, (giving $z_o = 3.8 \times 10^4$ g/cm^2/s) have been selected. Using these values, the reflection coefficient has been plotted as a function of ϕ for zero angle of incidence in Figure 26, where ϕ is a non-dimensional expression of frequency given by:

$$\phi = \frac{4\pi df}{c_o}. \qquad (24)$$

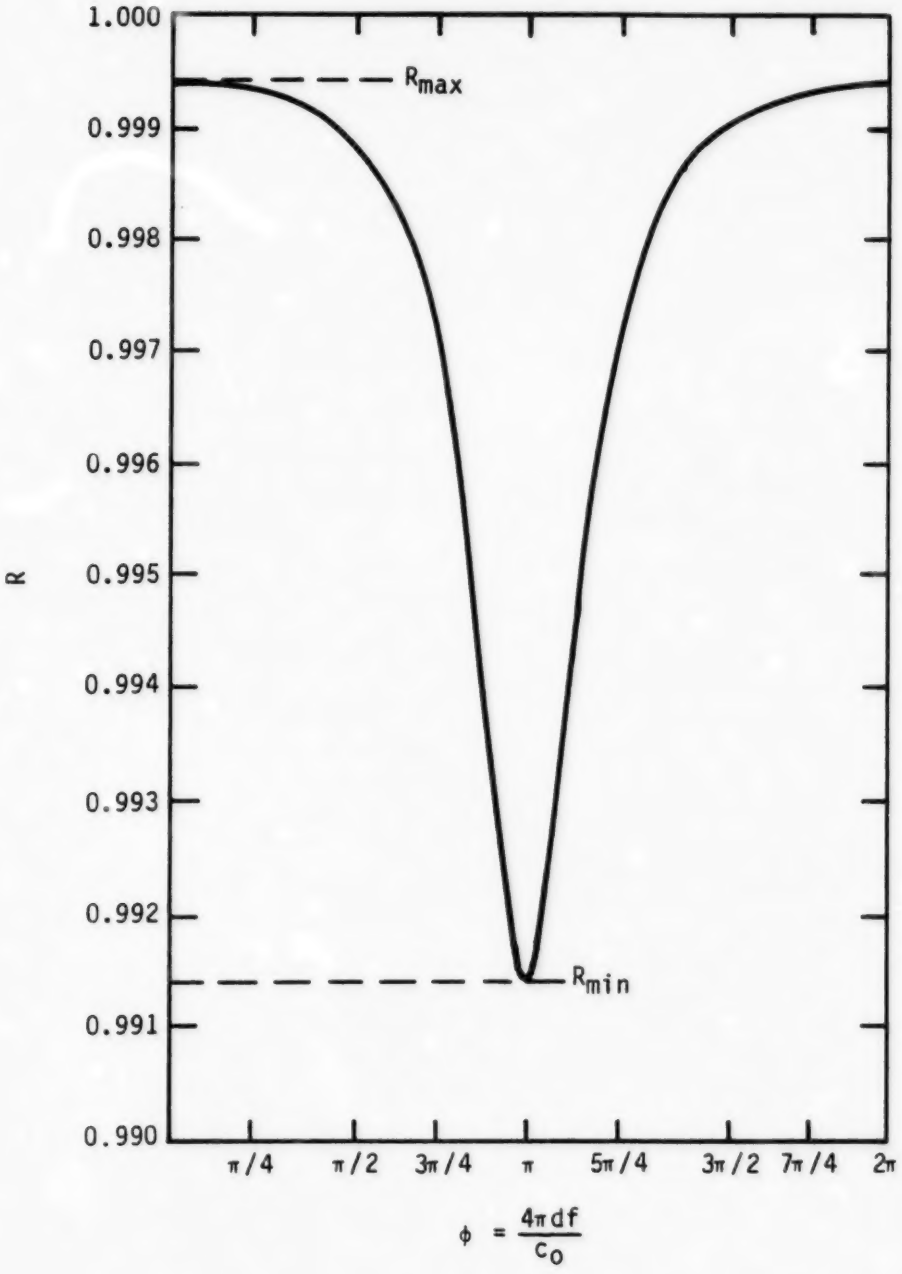

Fig. 26. Reflection coefficient plotted as a function of non-dimensionalized frequency: $z_o = 3.8 \times 10^4$ g/cm^2/s.

The shape of the curve in Figure 26 shows that, as expected, when $\phi \simeq \pi$ the reflection amplitude drops sharply compared to its value when ϕ is near 0 or 2π. Unfortunately, because of the large impedance mismatch between the oil and the air, the relative change in R between its maximum reflection amplitude R_{max} and the minimum reflection amplitude R_{min} is rather small, 1% at best. It is this small difference that must be observable by the acoustic receiver for the oil-thickness measurement technique to be feasible. To see how this difference is affected by different types of oils, the effect of changing the value of z_o on $(R_{max} - R_{min})/R_{max}$ is shown in Figure 27. The situation deteriorates as $z_o \rightarrow z_w$, at which point there is no reflection at the oil-water interface and, thus, no frequency dependence of R. We have also found that R is affected only slightly by changes in the angle of incidence, up to the point at which total reflection at the oil-water interface occurs ($\simeq 15°$).

POTENTIAL MEASUREMENT TECHNIQUES

Although ΔR is small, if it could be measured then z_o and c_o could be determined. Then, by measuring the frequencies at which the reflection coefficient is minimized, corresponding to $\phi = N\pi$ where N is an integer, the thickness of the oil could be determined. For example, if ΔR is measured to be 10^{-3}, then the impedance of the oil is 9×10^4 gm/cm^2/s. Using the oil density of 0.9 g/cm^3 yields a speed of sound $c_o = 1 \times 10^5$ cm/s. Continuing the example, if the lowest frequency at which there exists a minimum in the reflection coefficient is measured to be 50 KHz, then N=1 and $\phi = \pi$. From the definition of ϕ ($= 4\pi d/\lambda = 4\pi df/c_o$), the depth of the oil layer can now be calculated to be:

$$d = c_o/4f = (10^5 \text{cm/s})/(4 \times 5 \times 10^4\ s^{-1}) = 0.5\text{cm}.$$

Thus, as anticipated, all of the information required to determine the oil thickness is, in fact, contained in the reflected acoustic signal. However, a mechanism for accurately measuring R(f) over the relevant range of frequencies, and detecting tiny changes in its value, is required. Assuming transmitted frequencies can be as high as 10 MHz this technique will allow measurement of oil thickness as small as 25μm.

BROAD-BAND FREQUENCY DISTRIBUTION

As discussed previously, one method to detect oil is to measure the reflection coefficient of a broad distribution of frequencies. The technique investigated was to generate large-amplitude, distributed-frequency sound waves at the surface of the oil by directing a focused, high-energy laser pulse onto the oil.

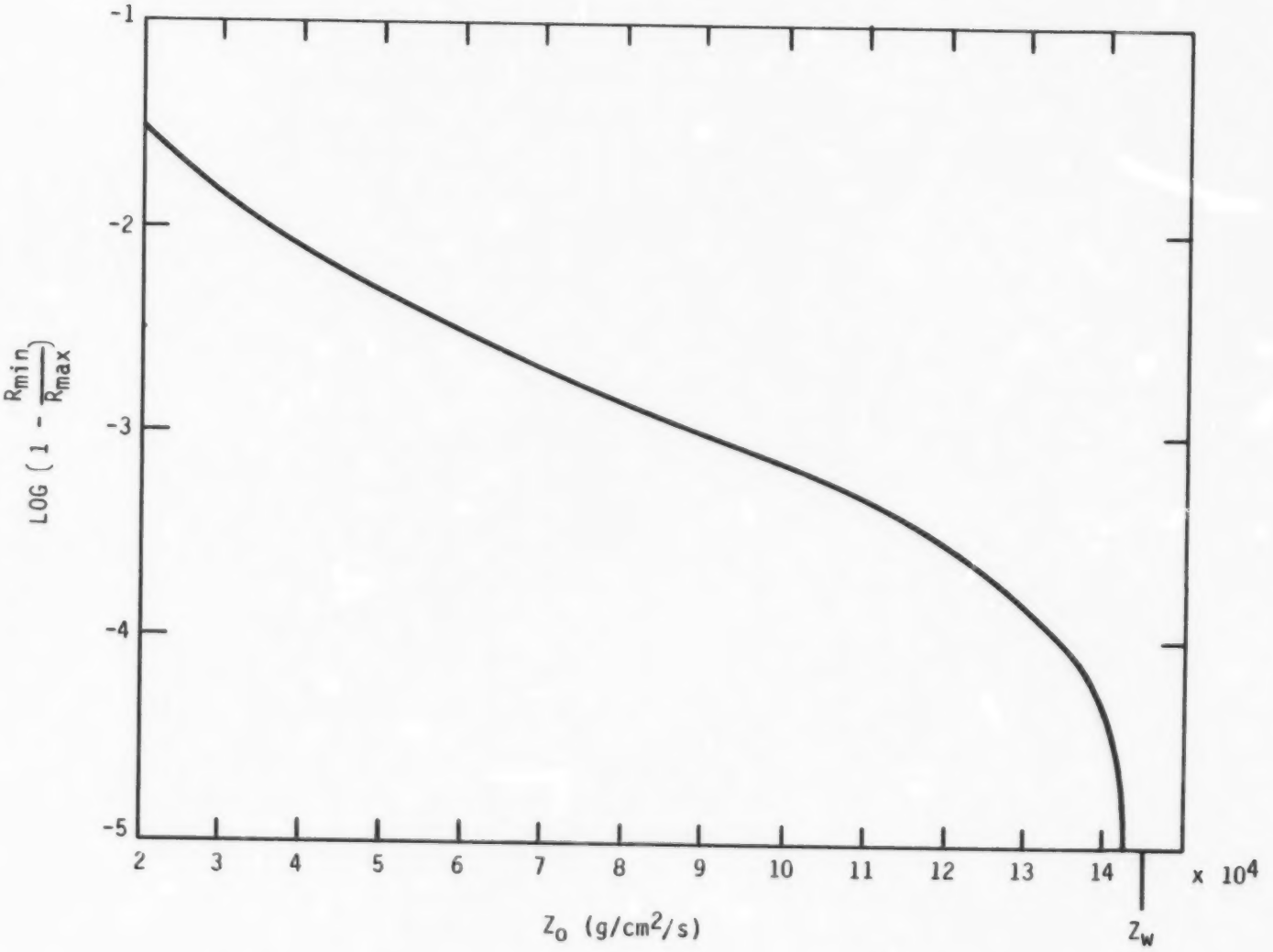

Fig. 27. Effect of changing the acoustic impedance of oil on the observable quantity $(R_{max} - R_{min})/R_{max}$.

This sudden concentration of energy creates a small explosion at the oil surface, generating a shock wave that can be thought of as a short, high-intensity burst of distributed-frequency sound. The reflections of this sound from the oil surface can also be detected with an acoustic antenna, and subjected to frequency analysis to determine the oil thickness. Filtering background noise from this signal can be accomplished by gating the receiver only during the time interval during which the signal is present.

Because it must be able to discern small frequency-dependent changes in the reflection coefficient, the laser-generated sound technique requires precise knowledge of the spectrum of sound waves created on each firing of the laser and an ability to measure this spectrum with an accuracy of a fraction of a percent. Figure 28 shows a typical spectrum of sound created by a similar laser irradiating a water surface, as reported by Nebolsine et al. (1982). It is seen that the spectrum is not very "clean," that is, the measured sound amplitude varies rather substantially with frequency. In addition, the spectra are not highly reproducible, and do not appear to contain much energy at frequencies above 0.3 MHz. Clearly, the noise in this spectrum far exceeds the anticipated signal, suggesting that it is highly unlikely that this technique would yield any usable information. Therefore this technique was not considered any further.

FREQUENCY-SCANNING TECHNIQUES

Another method for measuring the reflection coefficient is the frequency-scanning technique in which only one frequency is generated at a time. Ultra-high waves are generated and directed at the oil from a remote platform by means of an acoustic antenna. A similar antenna would then receive the reflections. Because it is difficult to focus sound waves, the amplitude of the transmitted wave will decrease rapidly as the distance from the source to the oil surface increases. Thus, the reflected waves will be rather weak, though, as already mentioned, they can be separated from background noise by filtering.

In contrast to the laser-generated sound technique, the frequency-scanning technique holds promise even though changes in R are small. Two methods are suggested. One involves lock-in amplifiers to measure the reflected wave and the second uses ultra-high-frequency FM waves for rapidly transmitting many frequencies.

Lock-in amplifiers can readily measure the amplitudes of reflected sound waves with an accuracy of 1 part in 10^4. In addition, the background noise at each frequency can be subtracted from the measured signal to give a true measure of the reflection coefficient. However, because this technique would require that the transmitter frequency be fixed for a period long enough for the lock-in amplifier to produce a reliable result, it could be tedious and time-consuming. Nevertheless, as long as $z_o/z_w < 13/15$, this technique should provide S/N ratios exceeding unity.

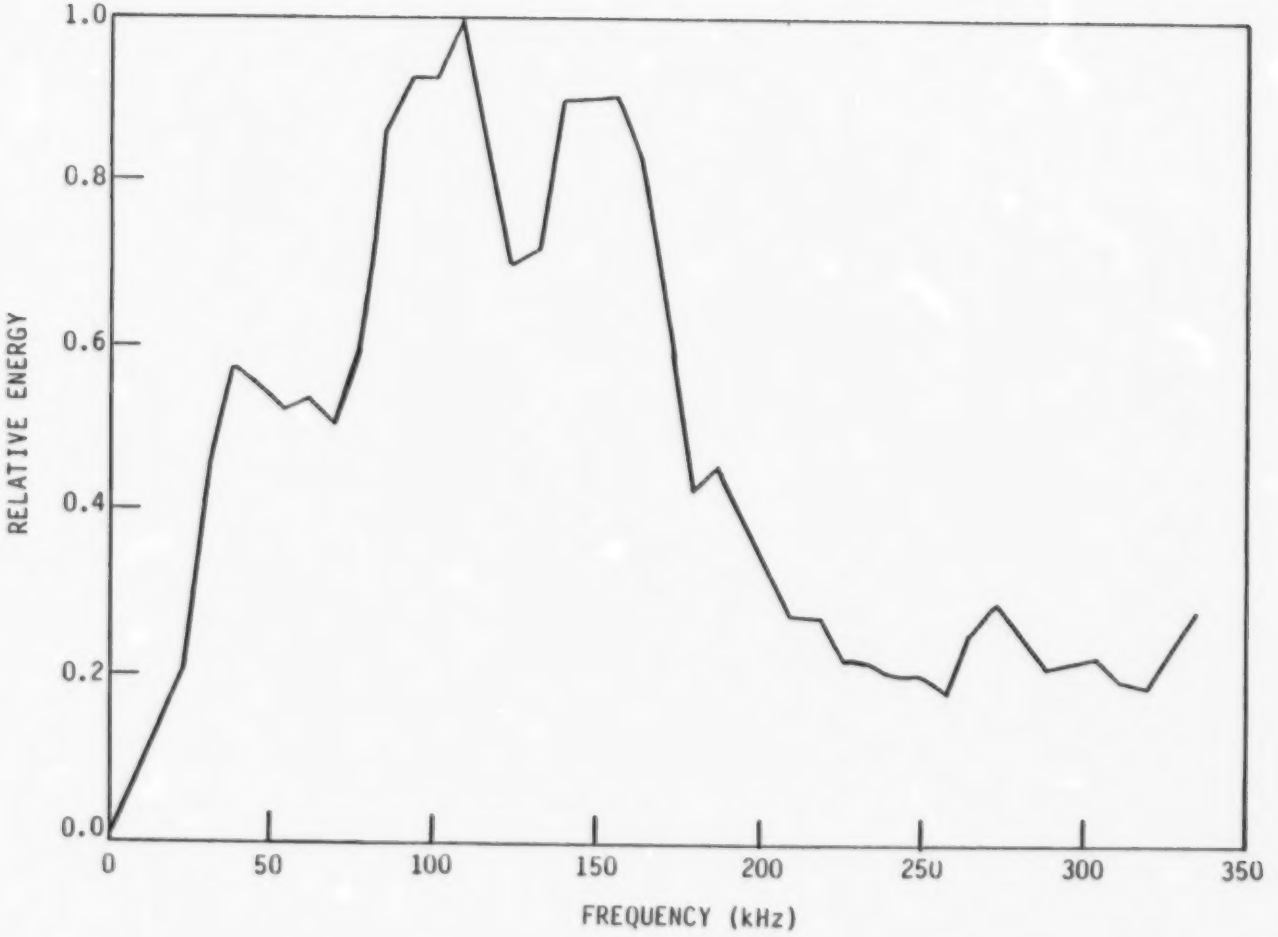

Fig. 28. Spectrum of acoustic energy generated by irradiating a water surface with a focused, pulsed CO_2 laser (Nebolsine et al. 1982).

This technique could be tested fairly easily using generally available laboratory equipment to measure the depths of oil layers that are at least several millimetres thick. For example, if the oil layer is 10 mm thick and its speed of sound 4×10^4 cm/s, then it is necessary to generate frequencies only as large as 20 KHz to map out a curve. Such frequencies can be generated with off-the-shelf audio equipment.

One could use a signal generator as the input to an audio amplifier, the output of which drives a speaker (or set of speakers). Some custom design would have to be incorporated into the speaker enclosures to enhance the directionality of their emissions. The sound would be directed towards an oil pool, and the reflections collected by a microphone, perhaps coupled to a parabolic acoustic collector to increase the collected energy. The received signal would be amplified using one of many available techniques (such as lock-in amplifiers) to limit the bandpass and thus to limit the noise. Frequencies would be scanned by manually adjusting the signal generator, making measurements at, say, every 500 Hz. These measurements would include the amplitude of the emitted signal and the amplitude of the detected reflected signal. The ratio of these two values is proportional to the reflection coefficient. Plotting this ratio as a function of frequency yields the information contained in Figure 29. It is then straightforward to determine ΔR, to calculate c_o, and thence, from the frequency at which R is minimized, to determine d. It is more difficult to specify equipment components that are capable of providing energy at the high- and ultra-high frequencies required for measuring thinner depths of oil, but the basic procedures are similar.

An alternate but similar technique is to use an ultra-high-frequency FM acoustic wave to scan rapidly across a range of frequencies which is large enough that, in a short period, many minima in the reflection coefficient are passed (see Figure 29). Figure 29 (a) shows an example of the excitation frequency varying in time, whereas the resulting temporal variation of the reflection coefficient is illustrated in Figure 29 (b). For example, if reflectance minima are found every 300 KHz, (300 KHz, 600 KHz, 900 KHz, etc.) and the frequency is varied by 30 MHz/s, then the reflection coefficient will be minimized every 10 ms. Frequency analysis of the reflected signal would, therefore, indicate significant energy at 100 Hz. Furthermore, the amplitude of this low-frequency component would be proportional to ΔR, and could be used to calculate the speed of sound in the oil. Thus, by detecting with what is essentially a superheterodyne receiver, only the low frequency reflections from an oiled water surface irradiated with an ultra-high-frequency FM acoustic wave, the depth of the oil can be deduced. We believe that this technique holds the most promise for this application. Note that the frequency range of interest is roughly the same as that used in radios, suggesting that the electronic technology required to construct appropriate transmitters and receivers is well developed. Coupling these electronic components to acoustic transmitters and receivers may, however, require a modest research effort.

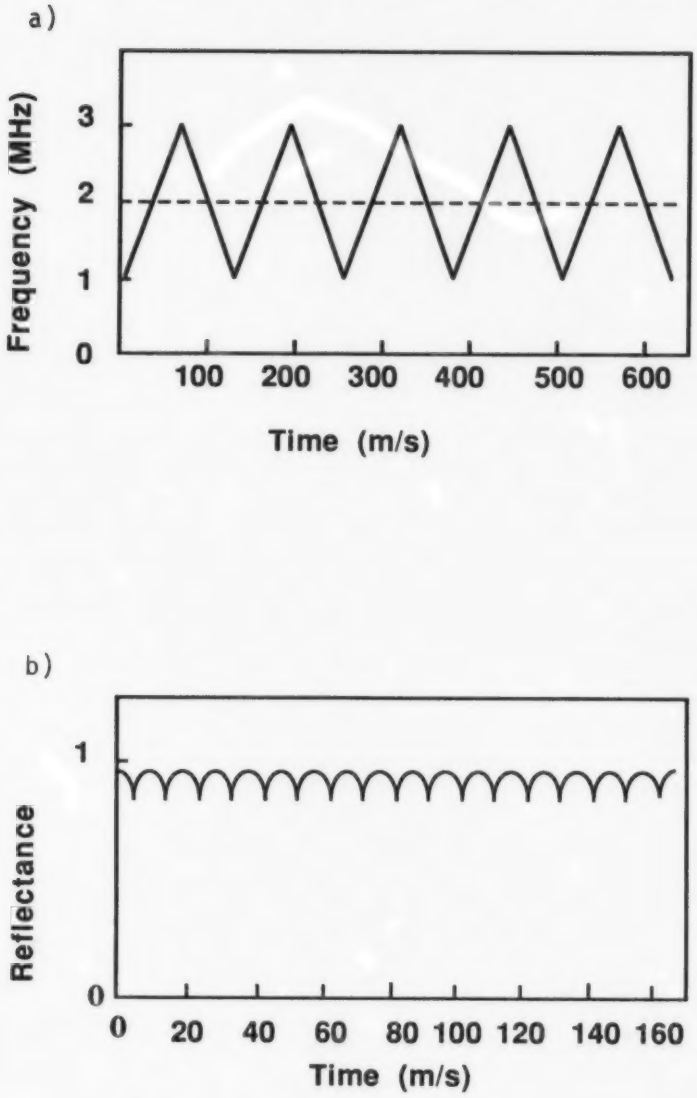

Fig. 29. Illustration of mechanism by which low-frequency modulation of reflected energy can be created by a frequency-modulated acoustic excitation: a) Excitation frequency versus time; b) Reflection coefficient versus time.

CONCLUSIONS

Based on the work performed during this study, and described in this report, the authors draw seven conclusions.

a) A theoretical study has been carried out to determine the feasibility of using acoustic surface waves to measure the thickness of oil layers on water. The study has shown that the propagation of such waves is possible, and that a physical mechanism exists which, in theory, should provide a means of measuring oil thickness. This mechanism involves the leakage of energy into the water substrate from the layer oscillations in the oil, because of the similar compressional wave responses of the oil and water. This phenomenon can be called "leaky-Lamb waves."

b) The numerical evaluations carried out have predicted quite high attenuation of the surface and layer vibrations in oil, but not so high as to invalidate the technique a priori. There is also a physical basis on which to believe that the actual attenuation will not be as high as those predicted by the theoretical model. The uncertainty arises from the physical assumptions necessary to extrapolate the experimental shear response data, and to convert these to Rayleigh wave velocity and attenuation data.

c) The experimental investigation demonstrated that Rayleigh waves in oil cannot be generated directly. A metal barrier technique has been devised, however, that allows oil to be detected easily using a simple amplitude measurement.

d) A frequency threshold for this effect could not be determined because of problems in producing frequencies below the initial frequency and in achieving thin uniform films of oil. Improvements are needed in transduction and instrumentation to study frequency effects.

e) The investigation of frequency-scanning techniques has shown that the relative change in the reflection coefficient of an oil layer between its maximum reflection amplitude and its minimum is only 1% at best. However even with such a small change in reflection coefficient, if an appropriate method could be found to find the frequencies at which the minima occur, this method could be used to determine oil thickness.

f) Laser-generated sound was found not to be a feasible means for generating a broad-band spectrum suitable for determining the frequency dependence of the reflection coefficient.

g) Two other possible methods for detecting minima in the reflection coefficient are suggested:

- fixing the transmitter frequency and detecting the reflected signal with a lock-in amplifier; and
- detection of low-frequency reflections when the oil surface is irradiated with an ultra-high-frequency FM acoustic wave.

The criteria stated in the first section of this report may also be reviewed to establish the compliance of the techniques considered in this study with the required characteristics. Both techniques are assessed in the following paragraphs.

a) Both techniques will probably satisfy the requirement for remote operation. However, the surface acoustic-waves technique requires the use of disposable and this might create some logistical problems depending on the number, sizes, and proximity of slicks to be quantified.

b) Both techniques tolerate, or account for, the variability in the type of oil. The first technique uses non-dimensionalized property dependence. However, a device of this type must be self-compensating so that it is independent of age or type of oil. The second technique, the frequency-dependent technique, is highly sensitive to type of oil. However, in the latter case the measurements can be used to deduce oil properties and to account for them.

c) The system resolution with respect to slick dimensions has not been clearly established in this study for any of the techniques. However, with disposable sensors, better resolution would necessitate using a larger number of sensors. For example, to integrate over an area 10 m by 10 m, if the accuracy of the measurement of the volume of oil allows the approximation of a constant oil thickness over a 2 m x 2 m square, then the volume of oil can be found by placing transducers in a grid of, say 2 m x 2 m square and by integrating over the transducer measurements. The resolution of the disposable sensors will be limited by the accuracy to which they can be placed. The cost of the sensors may also limit the number which can be deployed.

d) The effective thickness range should be established experimentally in the final analysis. From current information it appears that the surface-wave techniques could be effective in the range of interest. The frequency-scanning technique will probably be effective for layers as small as 25μm thick.

e) Additional requirements should be addressed at a more advanced stage of development.

RECOMMENDATIONS

It has been shown experimentally that oil can be detected by surface acoustic waves. Theory supports the argument that it should be possible to improve the detection capability to a determination of oil thickness. Therefore, further study is recommended. This study should concentrate on producing controllable oil-slick thickness in the laboratory for the purpose of calibrating and testing a sensor, and on producing a transduction arrangement that operates efficiently over a wide range of frequencies. Once this has been done, other parameters can be varied in a precise fashion to determine the frequency dependence, optimum barrier thickness, depth and material, and oil type, and temperature. The goal of further experimental work would be to establish to what extent the surface distortion effect is dependent on the initial thickness of the oil layer, and what modifications can be made to the apparatus and technique to enhance this dependence.

There are also many other related techniques for generating surface acoustic waves that could be evaluated. For instance, Rayleigh waves could be generated on a solid substrate and then reflected from the oil layer or transmitted across a narrow gap. Certainly the conclusion of the initial experimental evaluation is that acoustic measurement of oil thickness shows promise, and warrants a more rigorous evaluation.

The accuracy with which a grid of transducers could be positioned on an oil slick, and the cost of each transducer must be examined to determine operational feasibility of the deployable transducers.

Although the variance of the reflection coefficient is small, a frequency-dependent technique for measuring oil thickness is still theoretically possible. It is suggested that the two techniques - frequency-scanning using lock-in amplifiers, and detection of low-frequency reflections from an oil layer irradiated with FM acoustic waves - be further investigated to establish their feasibility.

This investigation would be mainly experimental if lock-in amplifiers were studied but would require the development of some specialized components for transmitting and receiving devices. In the case of the FM acoustic waves the study would probably concentrate on the development of a transmitter.

REFERENCES

Auld, B.A. 1973. Acoustic Fields and Waves in Solids. Vol. II. John Wiley and Sons, Inc., New York.

Barlow, A.J., and J. Lamb. 1959. The visco-elastic behaviour of lubricating oils under cyclic shearing stress. Proceedings Royal Society A 253, pp. 52-69.

Buist, I.A., and I. Bjerkelund. 1986. Oil in pack ice: preliminary results of three experimental spills. Proceedings, Ninth Annual Arctic Marine Oilspill Program Technical Seminar, Edmonton. pp. 379-398.

C-Core. 1981. Microwave systems for detecting oil slicks in ice-infested waters: Phase I - literature review and feasibility study. Environmental Protection Service Report No. EPS 3-EC-81-3.

Garret, B.P. and W.G. Tidmash. 1985. Evaluation of remote sensing technology for monitoring low volume oil discharges from offshore well sites. Proceedings, Eighth Annual Arctic Marine Oilspill Program Technical Seminar, Edmonton.

Hoge F.E. and R.N. Swift. 1980. Oil film thickness measurement using airborne laser-induced water raman backscatter. Applied Optics, 19, pp. 3269-3281.

Jones, H.W., and E.M. Yeatman. 1985. The visco-elastic properties of 'weathered' crude oil from the Beaufort Sea. Journal of the Acoustic Society of America. 78:801-802.

Jones, H.W., and H.W. Kwan. 1983. The detection of crude oil under seawater in the arctic ocean. Proceedings, Sixth Annual Arctic Marine Oilspill Program Technical Seminar. Edmonton.

Landau, L.D., and E.M. Lifshitz. 1959. Fluid Mechanics. Pergammon.

Mason, W.P., W.O. Baker, H.J. McSkimin, and J.H. Heiss. 1949. Measurement of shear elasticity and viscosity of liquids at ultrasonic frequencies. Physical Review 75:936-946.

McColl, W., Canadian Center for Remote Sensing, EMR, 1987. Private communication.

Nebolsine, P.E., T. Tanzawa, and L. Popper. 1982. Laser generated acoustic study. Report No. TR-301, Physical Sciences Inc., Andover MA 01810.

O'Neil, R.A., R.A. Neville, and V. Thomson. 1983. The Arctic and Marine Oilspill Program (AMOP) remote sensing study. Environment Canada Report No. EPS 4-EC-83-3.

Rayleigh, J.W.S. The theory of sound, Volume 1. Dover Publications Inc. New York.

Ristic, V.M. 1983. Principles of Acoustic Devices. John Wiley and Sons, New York.

Saffari, N., and L.J. Bond. April 1986. Body to Rayleigh wave mode-conversion at steps and slots. Submitted to the Journal of Non-destructive Evaluation.

Suzuki I. and K. Miki. 1984. Testing of oil skimmers developed in Japan for cold climates. Proceedings, Seventh Annual Arctic Marine Oilspill Program Technical Seminar, pp. 96-118.

Till, S.M., and R.A. O'Neil. 1985. Development of an airborne operational laser fluorosensor for use in the Canadian offshore and Arctic. Proceedings, Eighth Annual Arctic Marine Oilspill Program Technical Seminar, Edmonton.

BIBLIOGRAPHY

Brekhovskikh, L.M. 1960. Waves in Layered Media. Academic Press, Inc., New York.

Brower, N.G., D.E. Himberger, and W.G. Mayer. July 1979. Restrictions on the existence of leaky Rayleigh waves. IEEE Transactions on Sonics and Ultrasonics. Vol. Su-26, No.4.

Budreau, A.J., and P.H. Carr. March 1971. Temperature dependence of the attenuation of microwave frequency elastic surface waves in quartz. Applied Physics Letters. Vol. 18, No. 6.

Garret, B.P., R.M. Gershey, and D.R. Green. 1986. Evaluation of remote sensing sentinel instrumentation for detecting oil discharges from offshore platforms. Proceedings, Ninth Annual Arctic Marine Oilspill Program Technical Seminar, Edmonton.

Kinsler, L.E., A.R. Frey, A.B. Coppens, and J.V. Sanders. 1982. Fundamentals of acoustics. (Third Edition). John Wiley & Sons. New York.

Krasil'nikov, V.A., and V.V. Krylov. May-June 1979. Surface-tension dispersion of Rayleigh waves. Sov. Phys. Acoust. 25(3).

Krylov, V.V. September-October 1979. Rayleigh waves on smooth surfaces of arbitrary shape. Sov. Phys. Acoust. 25(5).

Lapin, A.D. September-October 1979. Reflection of a Rayleigh wave from periodic corrugations of a surface in oblique incidence. Sov. Phys. Acoust. 25(5).

Leung, W.P. August 1980. Demonstration of shear waves, Lamb waves, Rayleigh waves by mode conversion. American Journal of Physics.

Love, A.E.H. 1927. A treatise on the mathematical theory of elasticity. (Fourth Edition) Dover Publications Inc., New York.

Oliner, A.A. 1978. Acoustic Surface Waves. In Topics in Applied Physics, Vol. 24. Springer-Verlag, Berlin, Heidelberg, New York.

Pitts, L.E., T.J. Plona, and W.G. Mayer. August 1976. Theoretical similarities of Rayleigh and Lamb modes of vibration. Journal of the Acoustic Society of America. Vol. 60, No. 2.

Press, F., and J. Healy. November 1957. Absorption of Rayleigh waves in low-loss media. Journal of Applied Physics, Vol. 28, No. 11.

Salzmann, E., T. Plieninger, and K. Dransfeld. 1968. Attenuation of elastic surface waves in quartz at frequencies of 316 MHz and 1047 MHz. Applied Physics Letters, Vol. 13, No. 1.

Slobodnik, A.J.Jr., P.H. Carr, and A.J. Budreau. 1974. Microwave frequency acoustic surface-wave loss mechanisms on $LiNbO_2$. Journal of Applied Physics, Vol. 41, No. 11.

Wallis, R.F., D.L. Mills, and A.A. Maradudin. 1979. Attenuation of Rayleigh waves by point defects. Physical Review B, Vol. 19, No. 8.

Zahorsi, S. 1983. Remarks on Rayleigh-type waves in visco-elastic incompressible fluids. Warszawa. Arch. Mech., 35(4):491-496.